Magnetic field structure in the ICM and its effects

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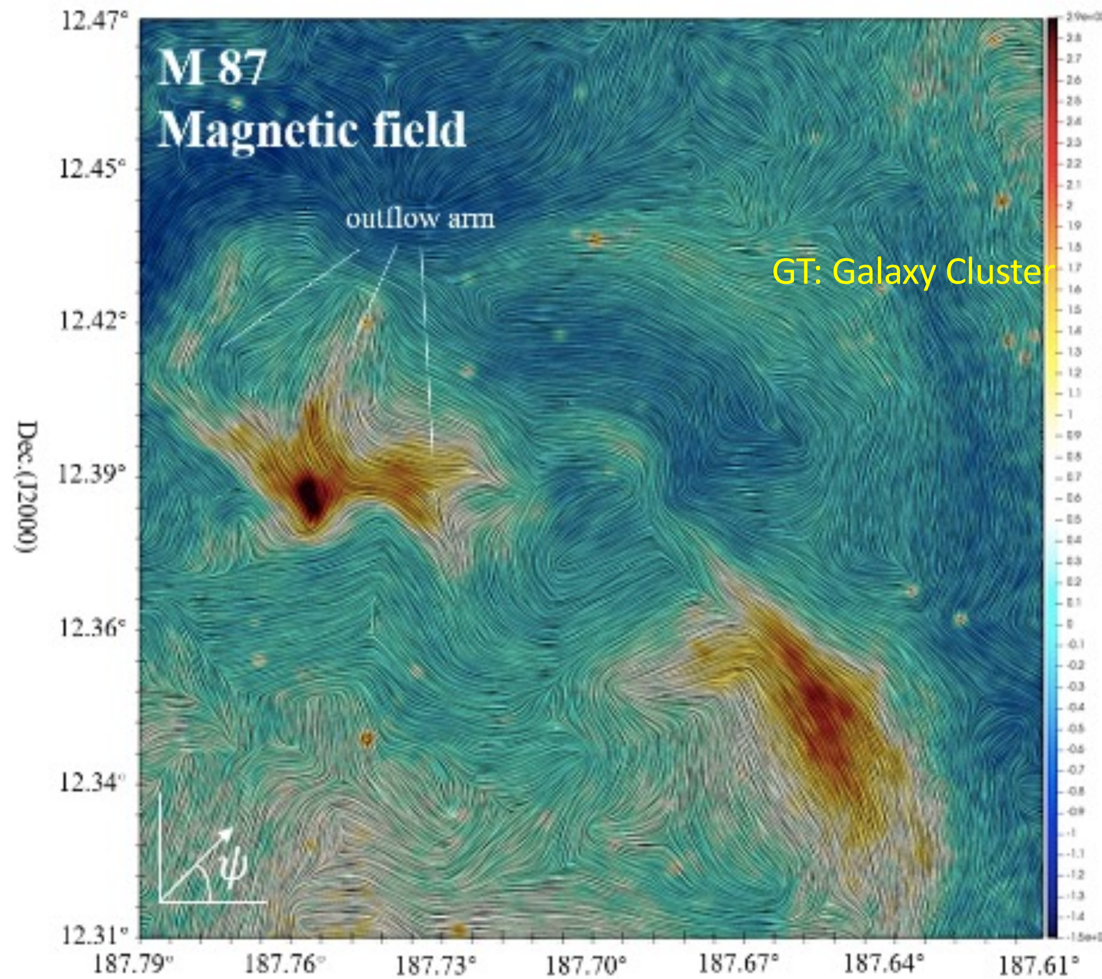
University of Wisconsin-Madison



Special Thanks: Gianfranco Brunetti, Annalisa Bonafede, Chiara Stuardi,
Yue Hue, Li Yuan, G-M Lou, Irina Zhuravleva, Siyao Xu

Please note Yue Hu, Van Vleck Prize Winner:

Is going to get PhD degree with me in 2023 and will apply for positions this Fall

Magnetic fields radically change the properties of ICM plasmas

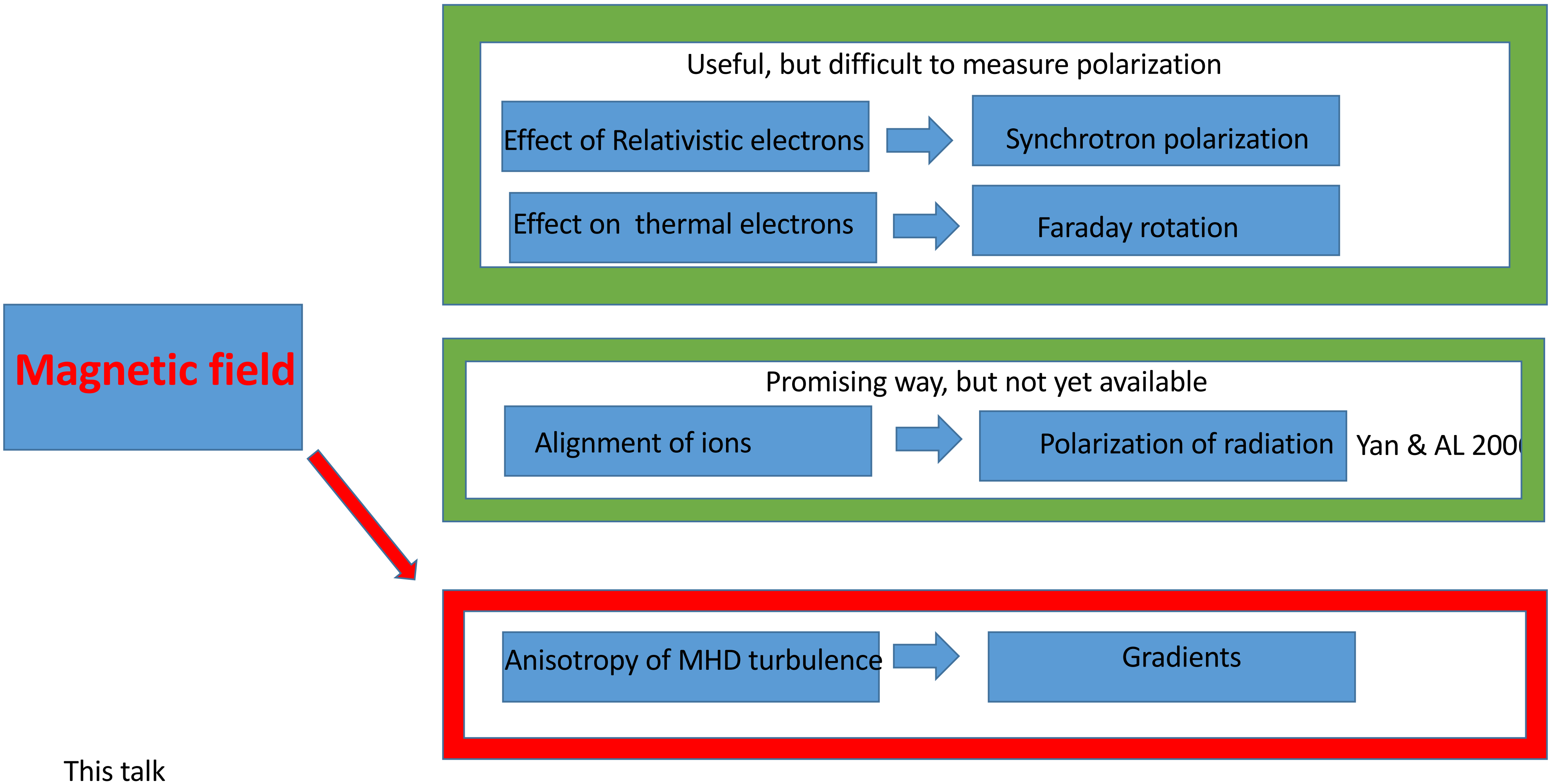
For instance:

1. Effect on thermal conductivity
2. Transfer from collisionless to effectively collisional state
3. Coupling plasmas with cosmic rays

Questions to address:

1. How can one study magnetic fields?
2. What are the quantitative effects?

Clusters' magnetic fields: how do we measure if we don't see



Gradient Technique (GT): foundations and incarnations

Turbulent reconnection
AL & Vishanic 1999

Theory of statistics of fluctuations in Position-Position-Velocity (PPV) space
AL & Pogosyan 2000
Kandel, AL & Pogosyan 2017

Velocity Centroid Gradients (VCGs)
GS & AL 2017,
Yuen & AL 2017

Velocity Channel Gradients (VChGs)
AL & Yuen 2017

Theory of synchrotron intensity fluctuations
AL & Pogosyan 2012

Synchrotron Intensity Gradients (SIGs)
AL & Yuen 2017

Theory of statistics of synchrotron polarization fluctuations in Position-Position-Frequency (PPF) space
AL & Pogosyan 2016

Synchrotron Polarization Gradients (SPGs, i.e gradients of P and (SPDGs, i.e. gradients of $\frac{dP}{d\lambda^2}$)

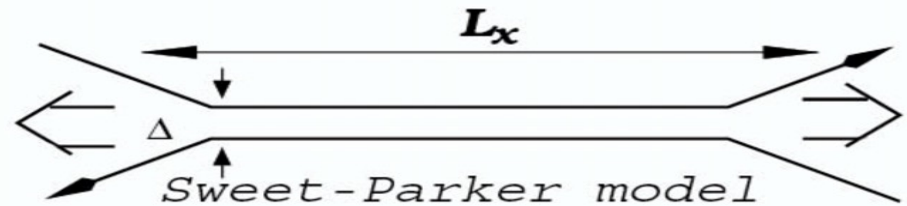
AL & Yuen 2018

Full theory of gradients is in AL, Yuen & Pogosyan 2022

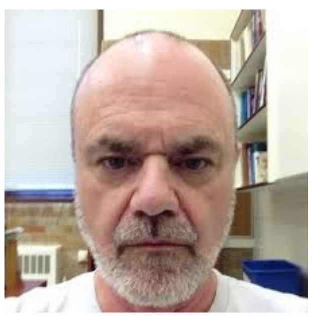
Turbulent magnetic fields reconnect fast

LV99 prediction:

$$V_{rec} \approx V_A \left(\frac{V_{inj}}{V_A}\right)^2 \left(\frac{L_{inj}}{L_y}\right)^{1/2}$$



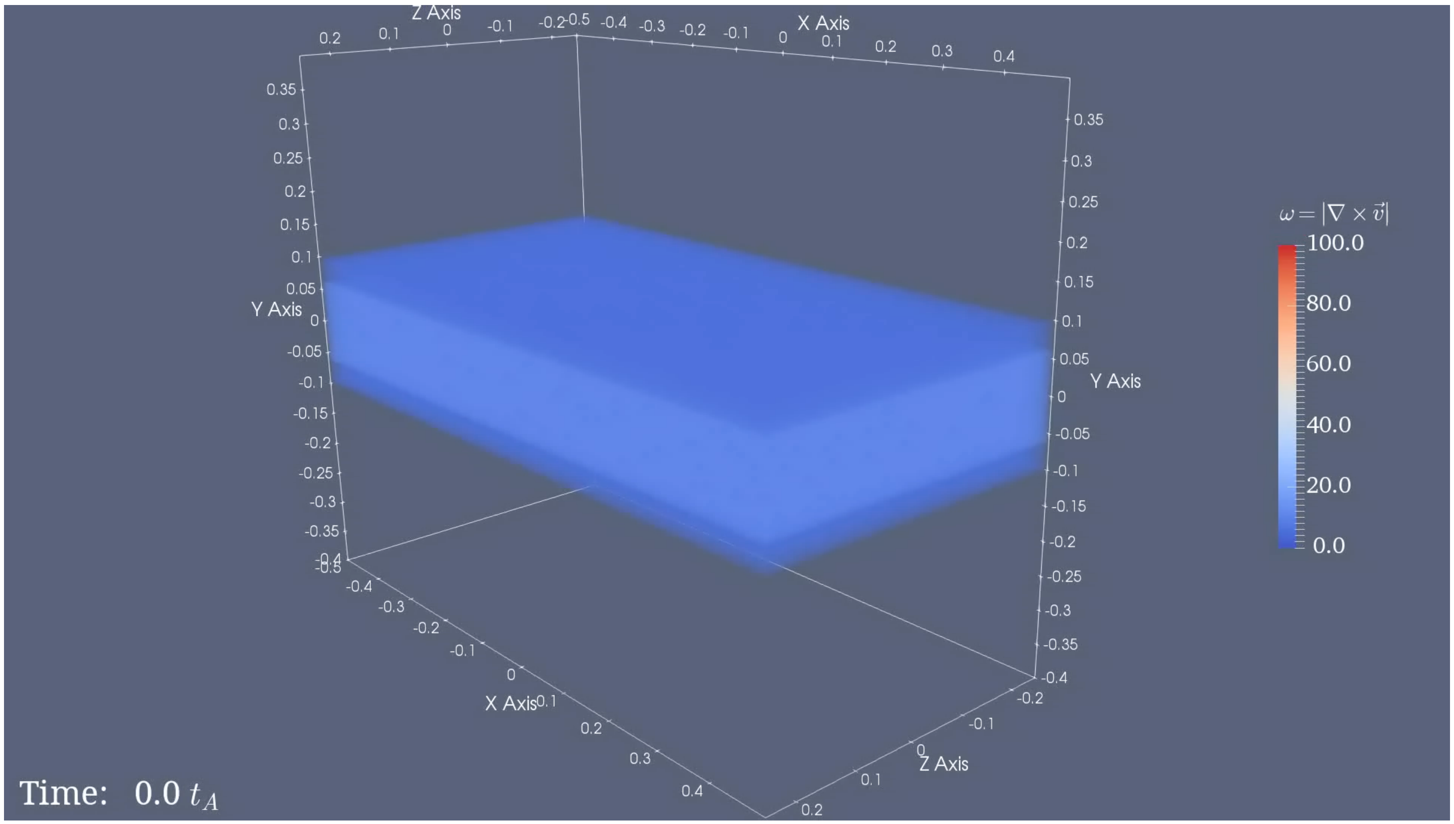
$$V_{rec} = V_A \frac{\Delta}{L_x}$$



E. Vishniac

AL & Vishniac (1999)

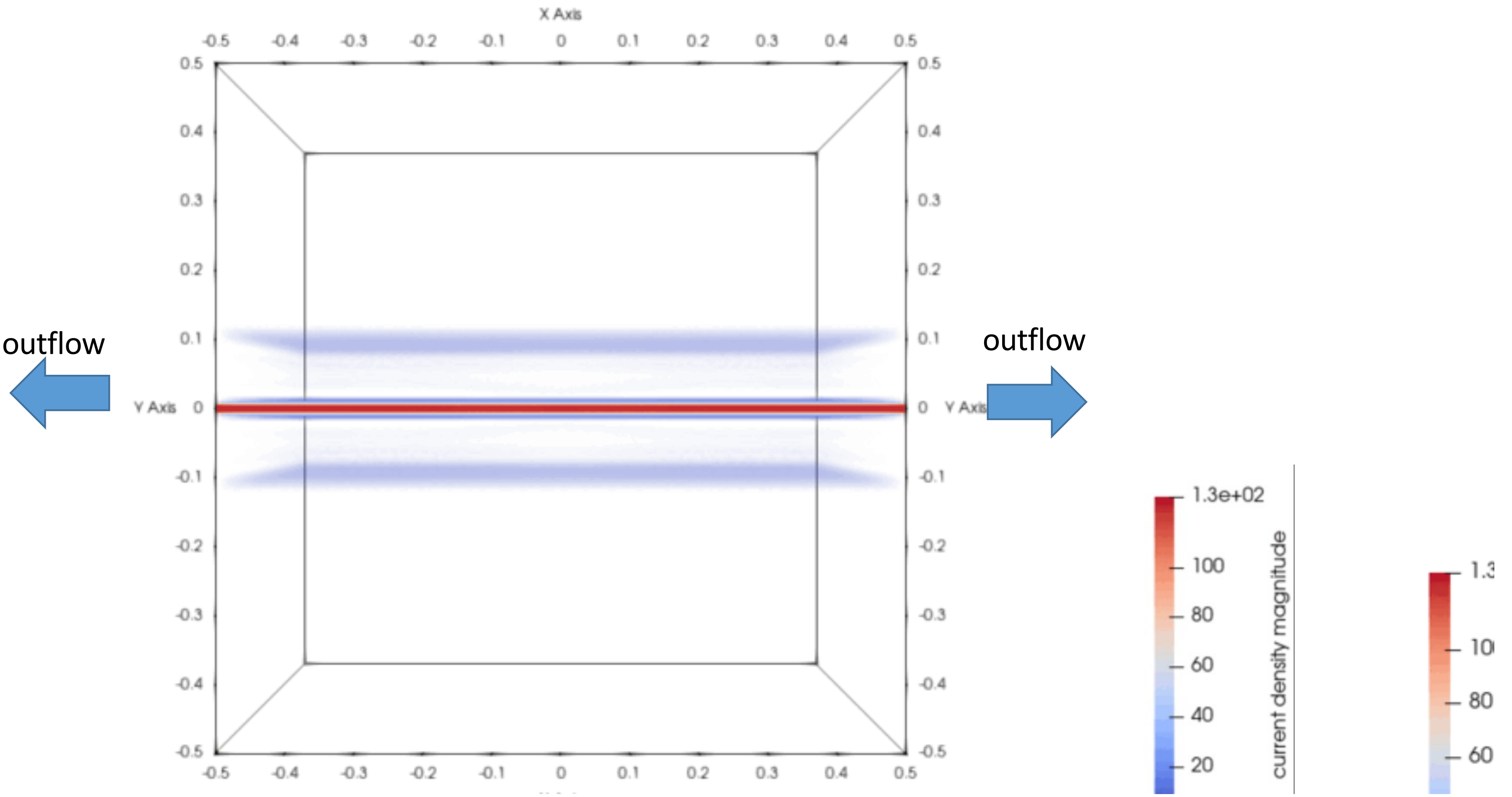
Turbulence is inevitable in 3D reconnection: development of turbulence through Kelvin-Helmholz instability



Kowal et al. 2017, 2020

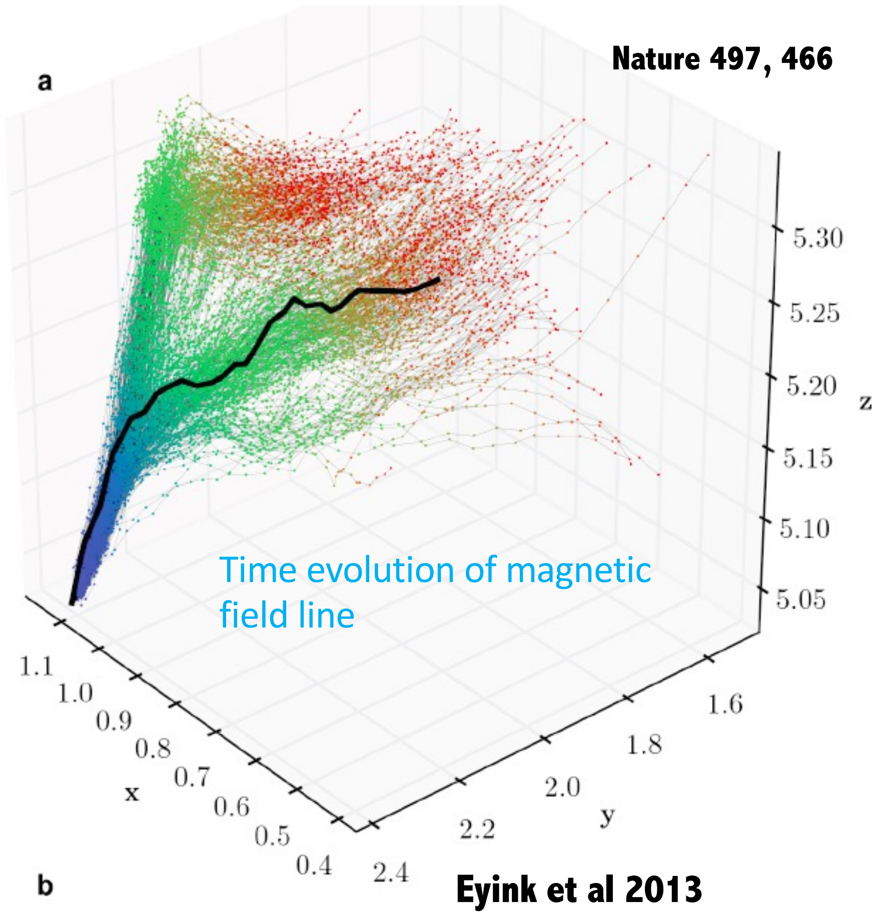
Example: flares of reconnection happen in low beta plasmas

Kowal et al. 2022



Magnetic flux freezing is violated in turbulence due to turbulent reconnection

Nature 497, 466

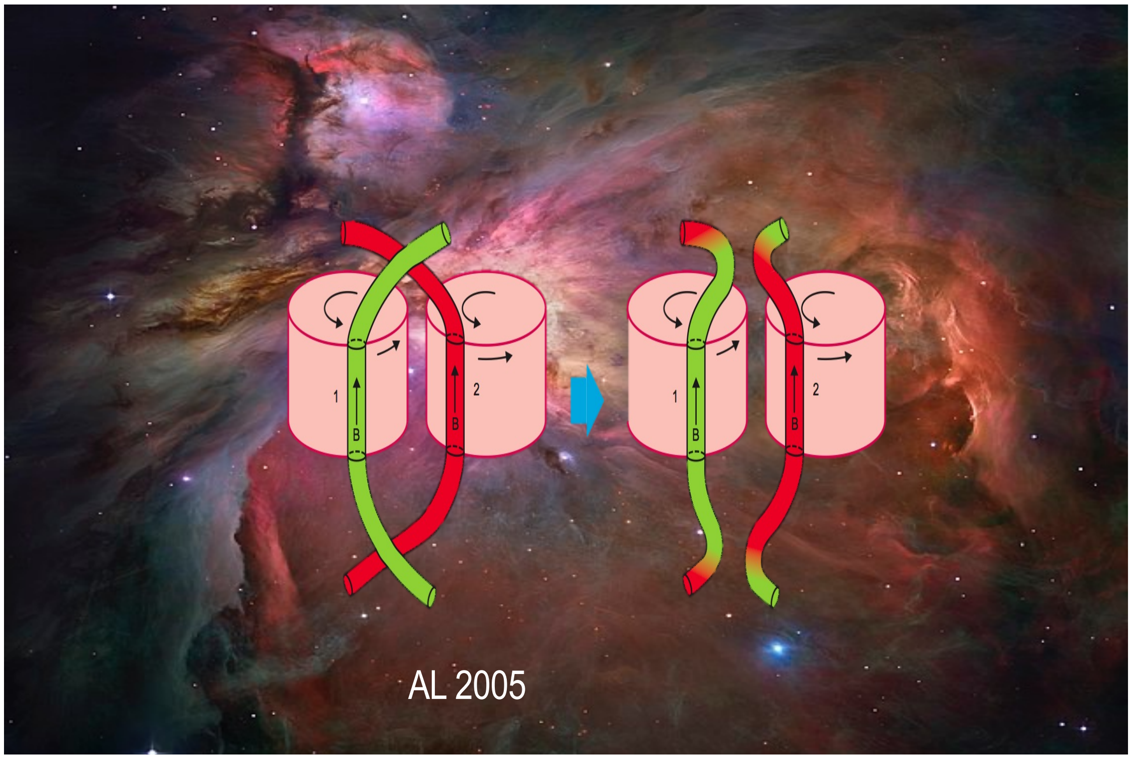


Eyink et al 2013

Alfven theorem: magnetic field line can only be deformed

Reality: any given magnetic field line has billions of parents

Flux conservation (Alfven theorem 1942) is violated in any turbulent medium

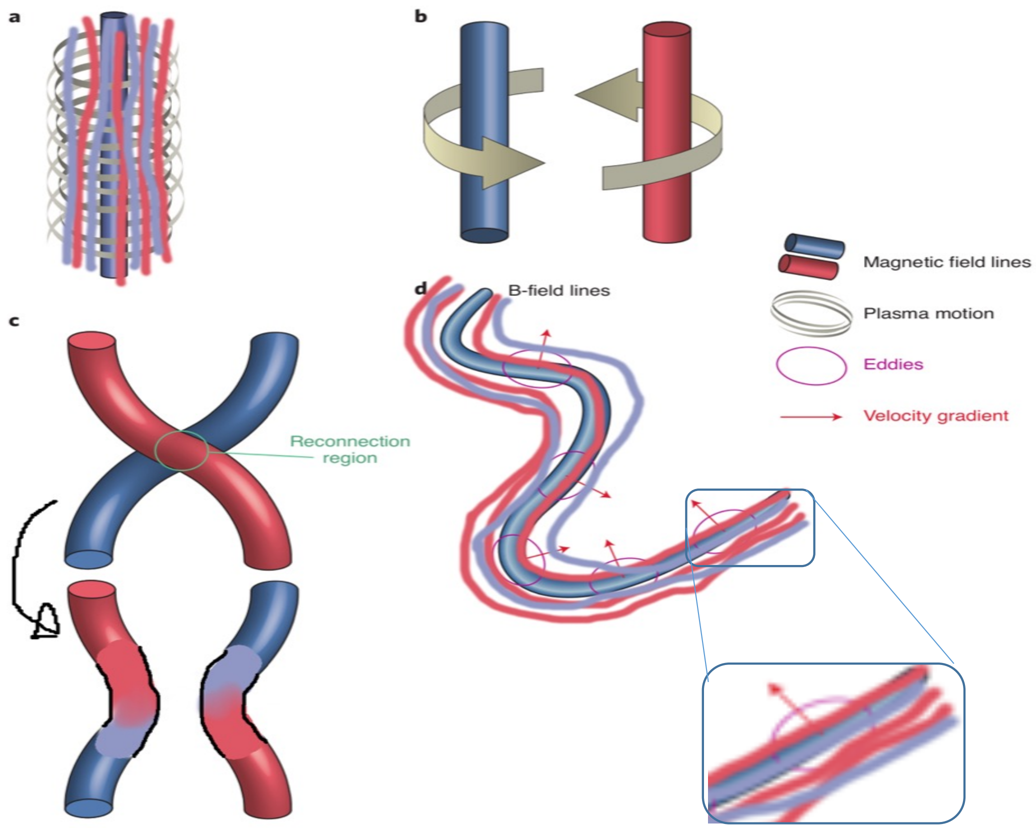


Consequence: reconnection diffusion

H. Alfven

Reconnection diffusion induces heat transfer

Turbulent reconnection happens within an eddy turnover time, it favors eddies aligned with B-field: Gradients are perpendicular to local B-field



Turbulent reconnection (AL & Vishniac 1999)

Types of Gradients:

1. Velocity gradients
2. Synchrotron intensity gradients
3. Synchrotron polarization gradients
4. Faraday rotation gradients

For subsonic turbulence, density acts as a passive scalar reflecting velocity statistics.

5. Density gradients

Fact Two: Turbulent gradients are dominated by the smallest resolved scales

If we measure below the turbulence injection scale

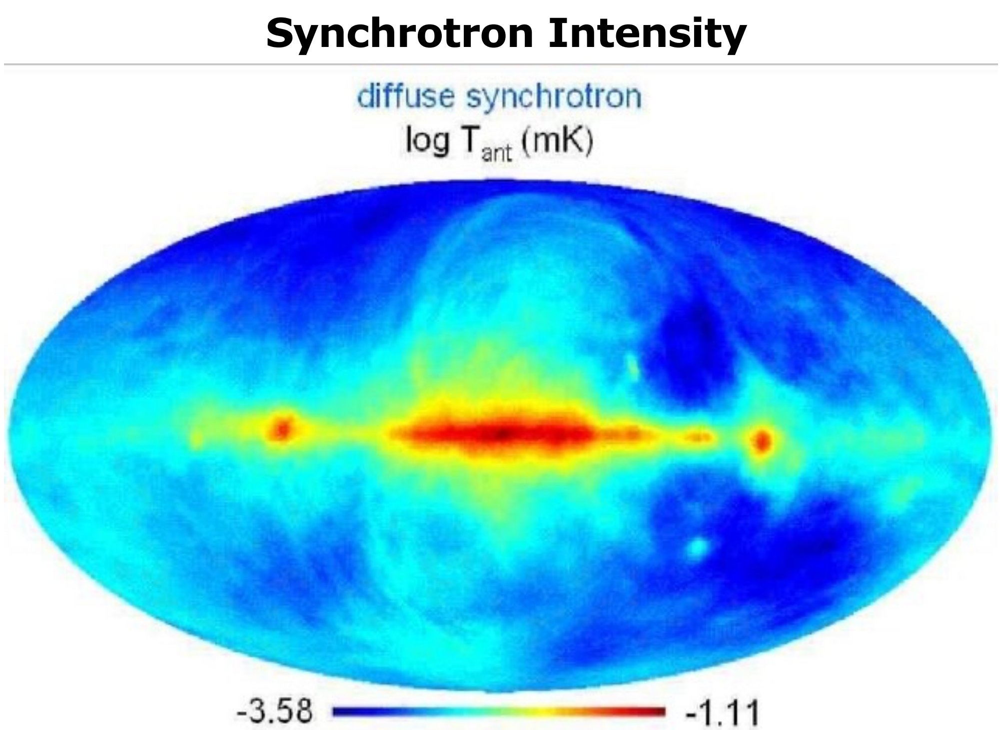
For velocity $v_l \sim l_\perp^{1/3}$

Gradient $\perp$ to B $v_l / l_\perp \sim l_\perp^{1/3} / l_\perp = l_\perp^{-2/3}$

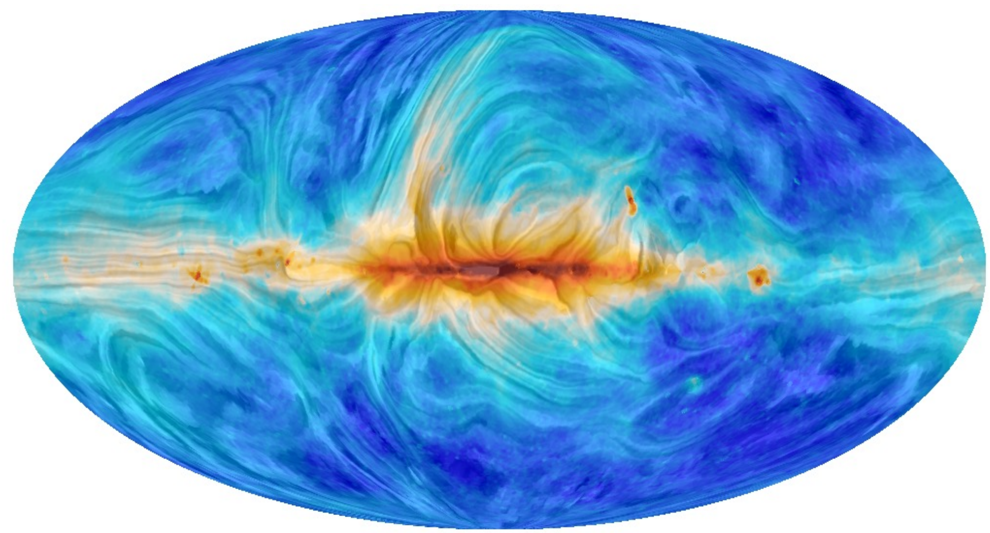
Large scale shear does not affect gradients, gradients are dominated by motions at the smallest resolved turbulence scales

For Alfvenic motions, B and V are interchangeable, thus synchrotron intensity gradients trace B.
For subsonic turbulence, density statistics mimics velocity statistics, thus intensity gradients trace B.

Can we directly get magnetic field orientation from synchrotron intensity

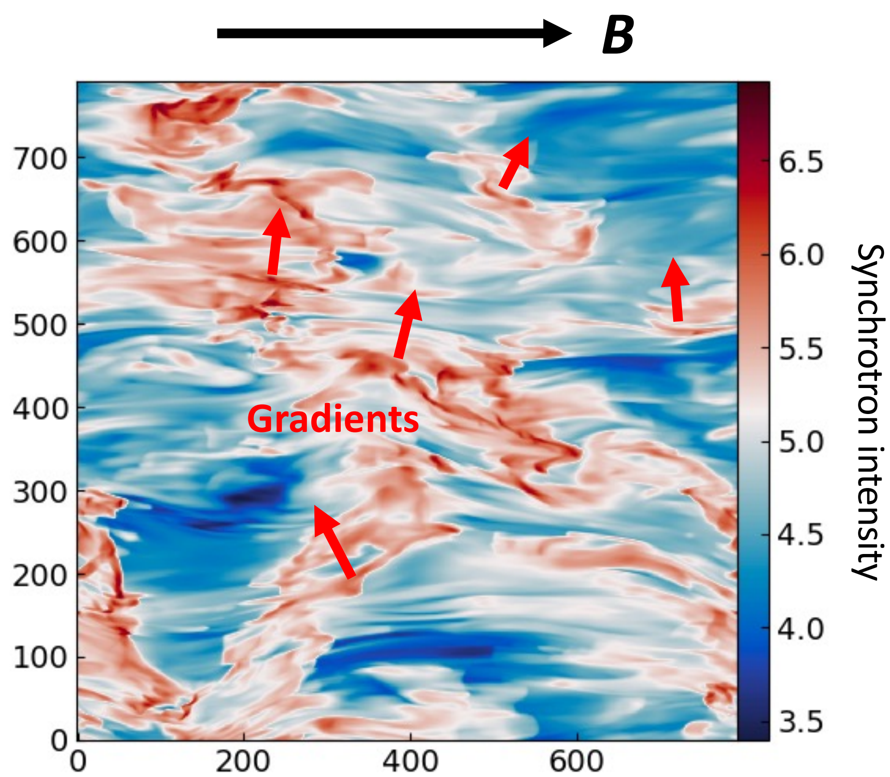


Magnetic field lines traced by synchrotron polarization



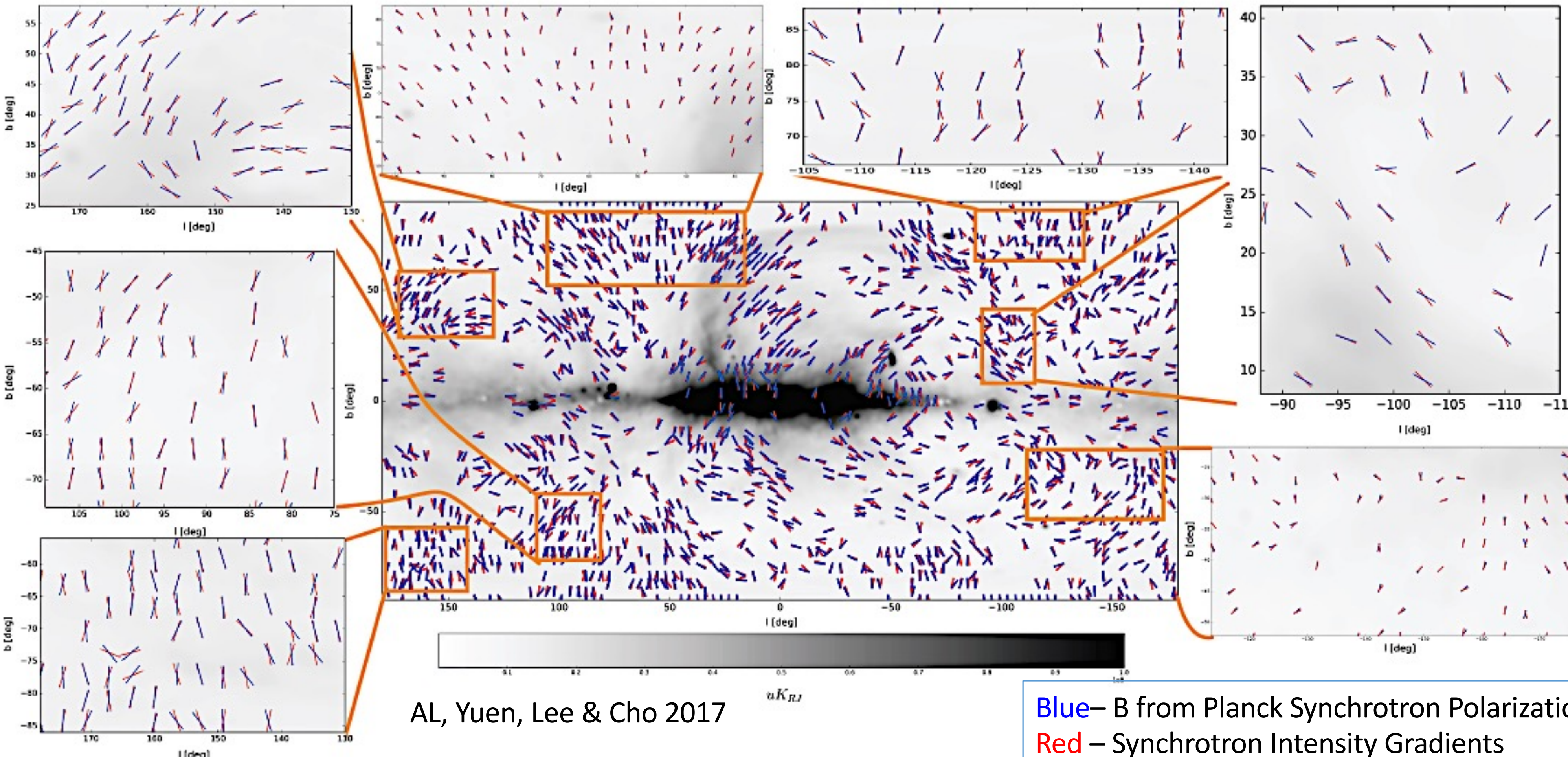
Planck collaboration

Visualization of synchrotron intensities in MHD simulations



AL et al. 2017

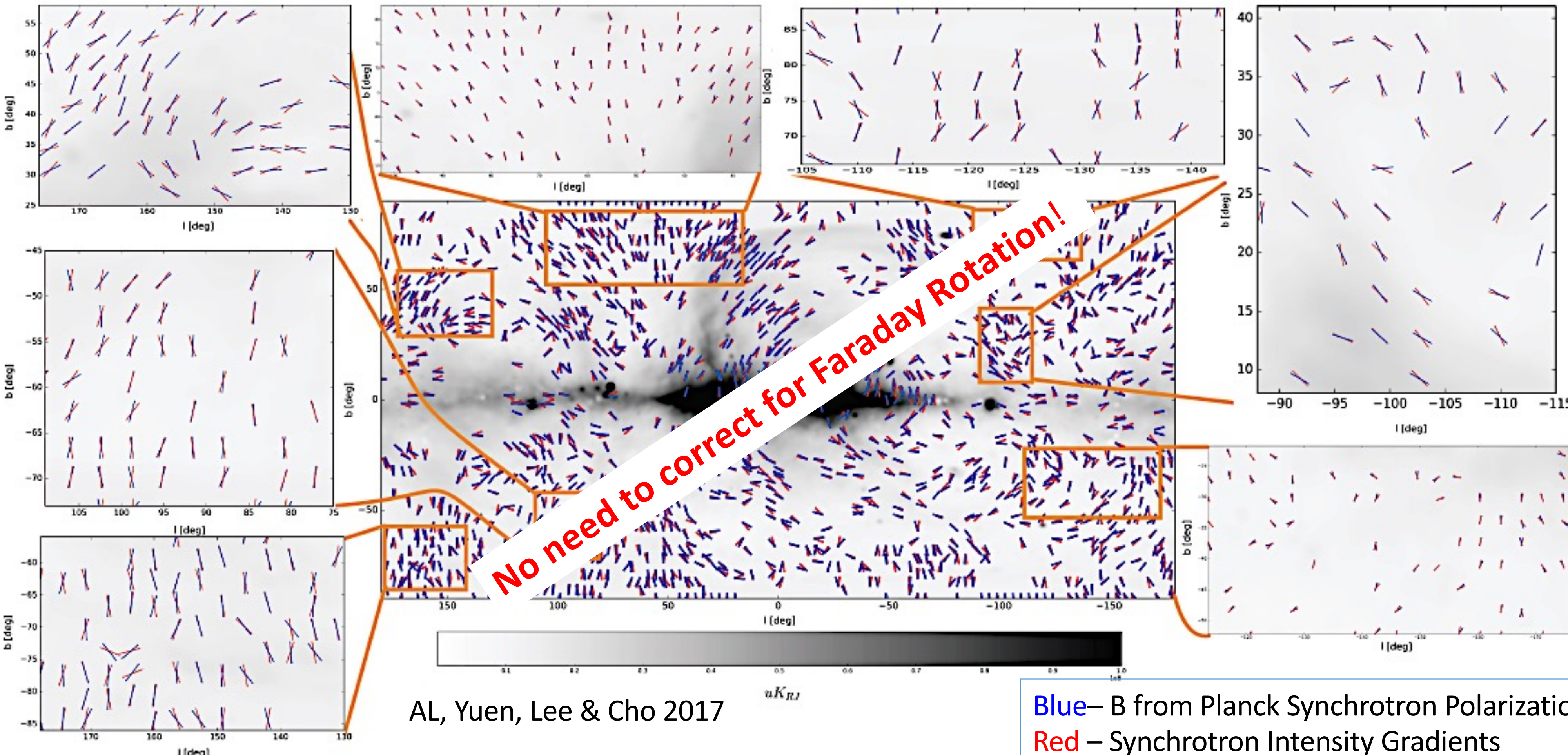
The maximum synchrotron intensity gradient (rotated by 90°) aligned with magnetic field



AL, Yuen, Lee & Cho 2017

Blue – B from Planck Synchrotron Polarization
Red – Synchrotron Intensity Gradients

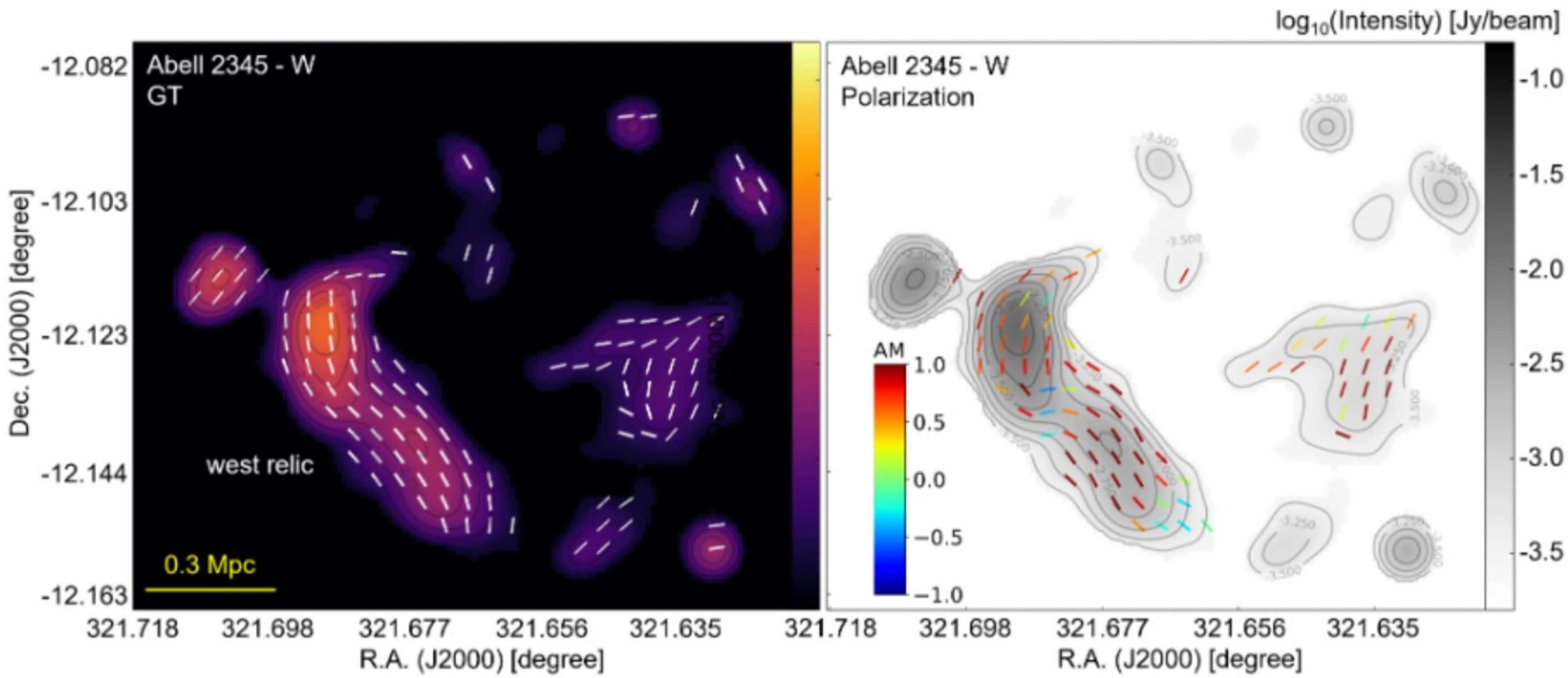
The maximum synchrotron intensity gradient (rotated by 90°) aligned with magnetic field



AL, Yuen, Lee & Cho 2017

Blue– B from Planck Synchrotron Polarization
Red – Synchrotron Intensity Gradients

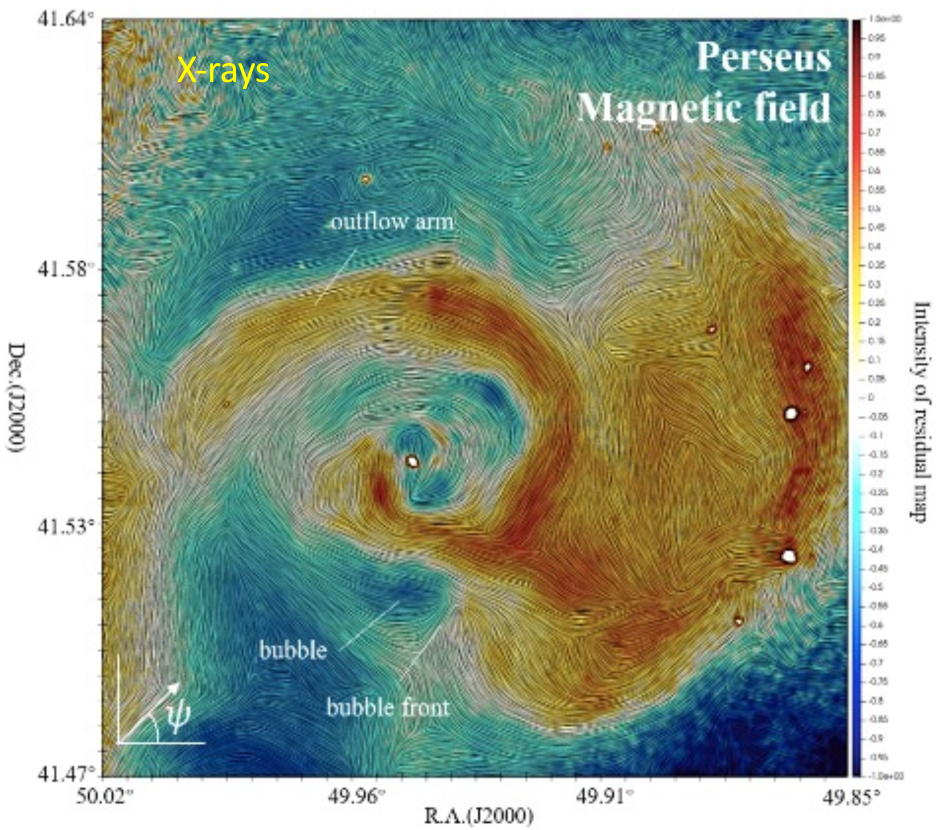
Good correspondence with the existing polarization

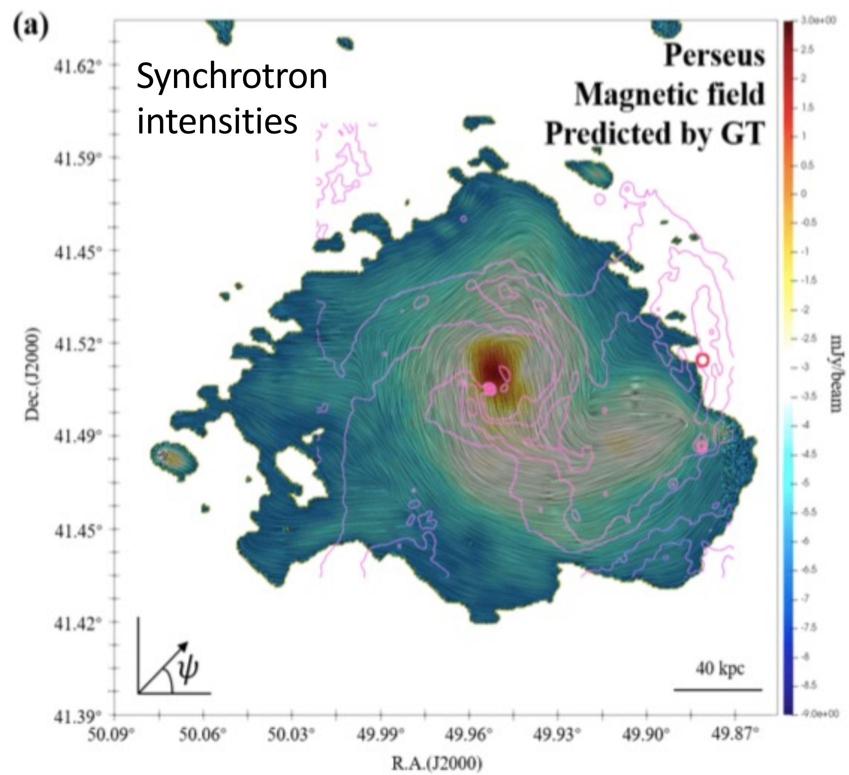


Yue Hu

Hu et al. 2022

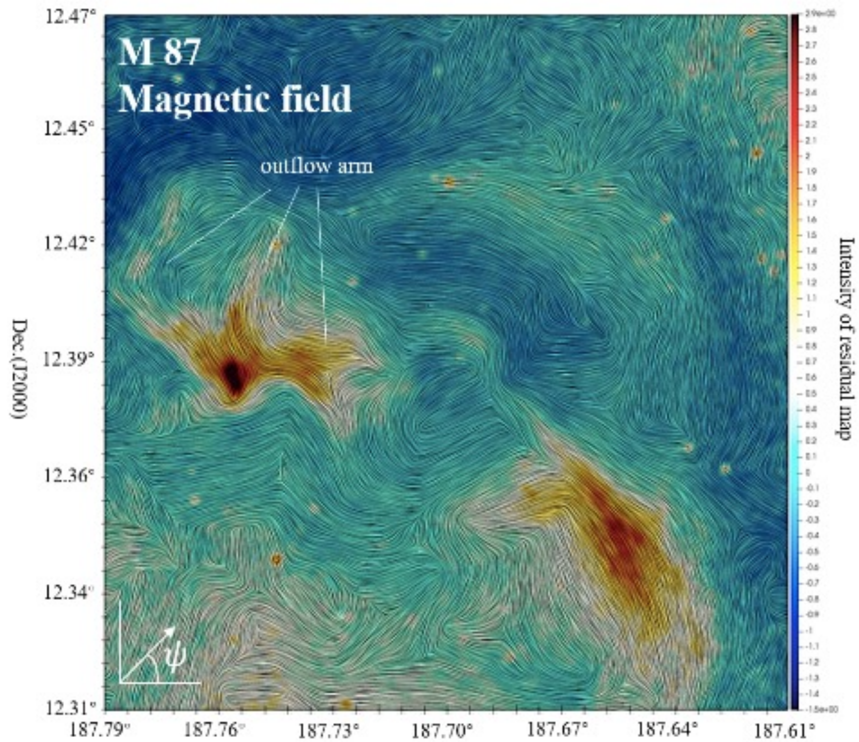
Density for low sonic Mach numbers reflects the velocity pattern. X-ray and synchrotron intensity gradients reveal magnetic field directions in galaxy clusters





Hu et al. 2020

The magnetic field structure of other clusters was obtained using X-ray and synchrotron emission images

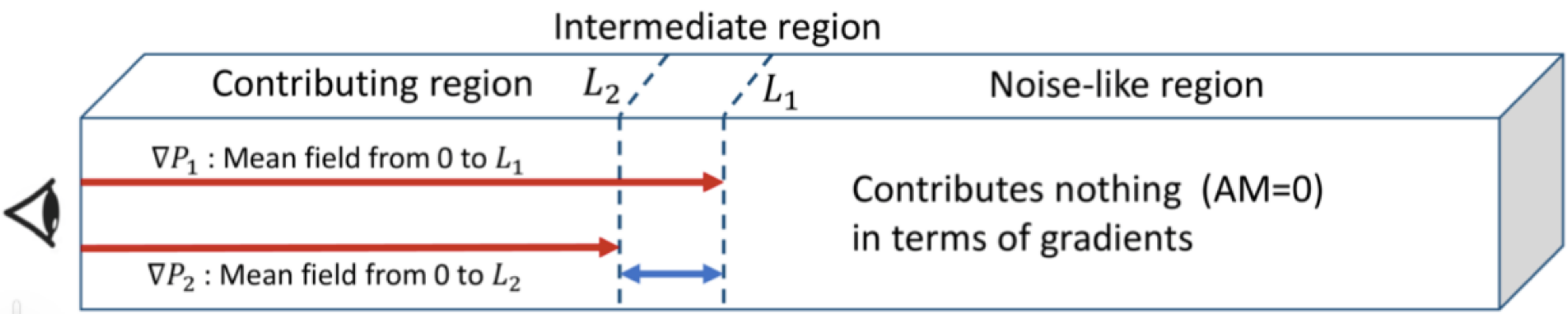


Hu et al. 2020

And many more in a new paper by Hu et al. 2022 using synchrotron emission

The next step will be the tomography of magnetic field using gradients

Faraday depolarization effect provides the boundary up to which the polarized synchrotron is sampled: Allows to study 3D distribution



$$\nabla(\Delta P) = \nabla \int_{L_2}^{L_1} dz P_i \, e^{2i\lambda_1^2 \phi(z)}$$

tells the mean field in slice $l \in [L_2, L_1]$

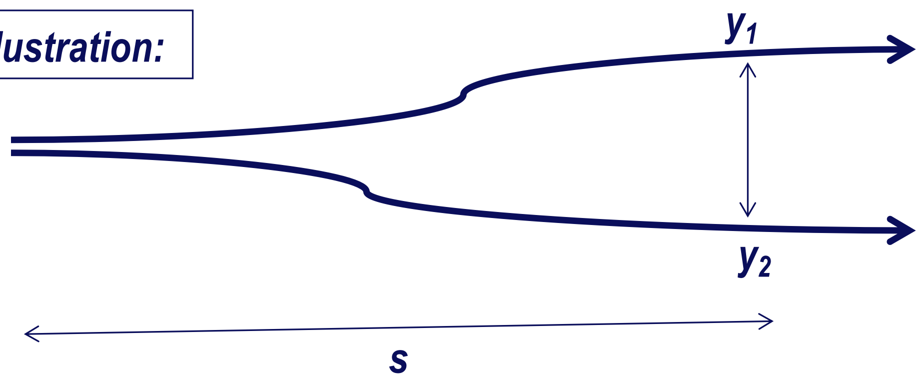
Unlike polarization directions the directions of the gradients of |P| are not affected by Faraday rotation. This provides a unique way to may the perpendicular to line of sight B-filed in 3D.

Suggested in AL & Yuen 2018. Tested successfully in Ho et al. 2020

Properties of the magnetic field that must be accounted for: effects of heat conduction and cosmic ray physics

Diffusion of electrons along magnetic field induces thermal conductivity

Simplified illustration:

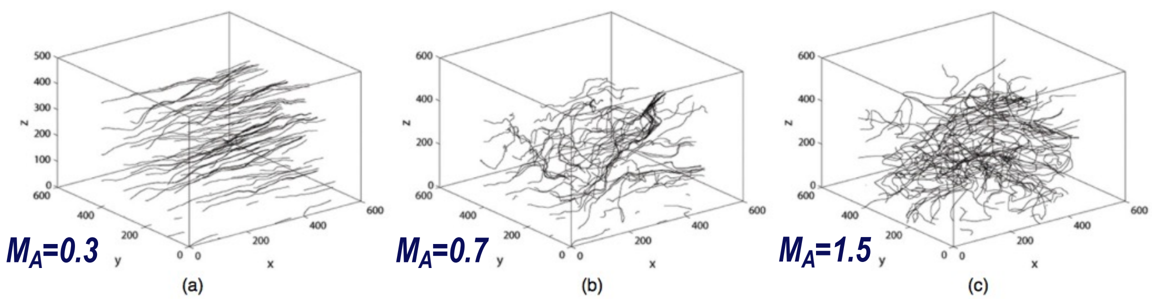


For y<injection scale

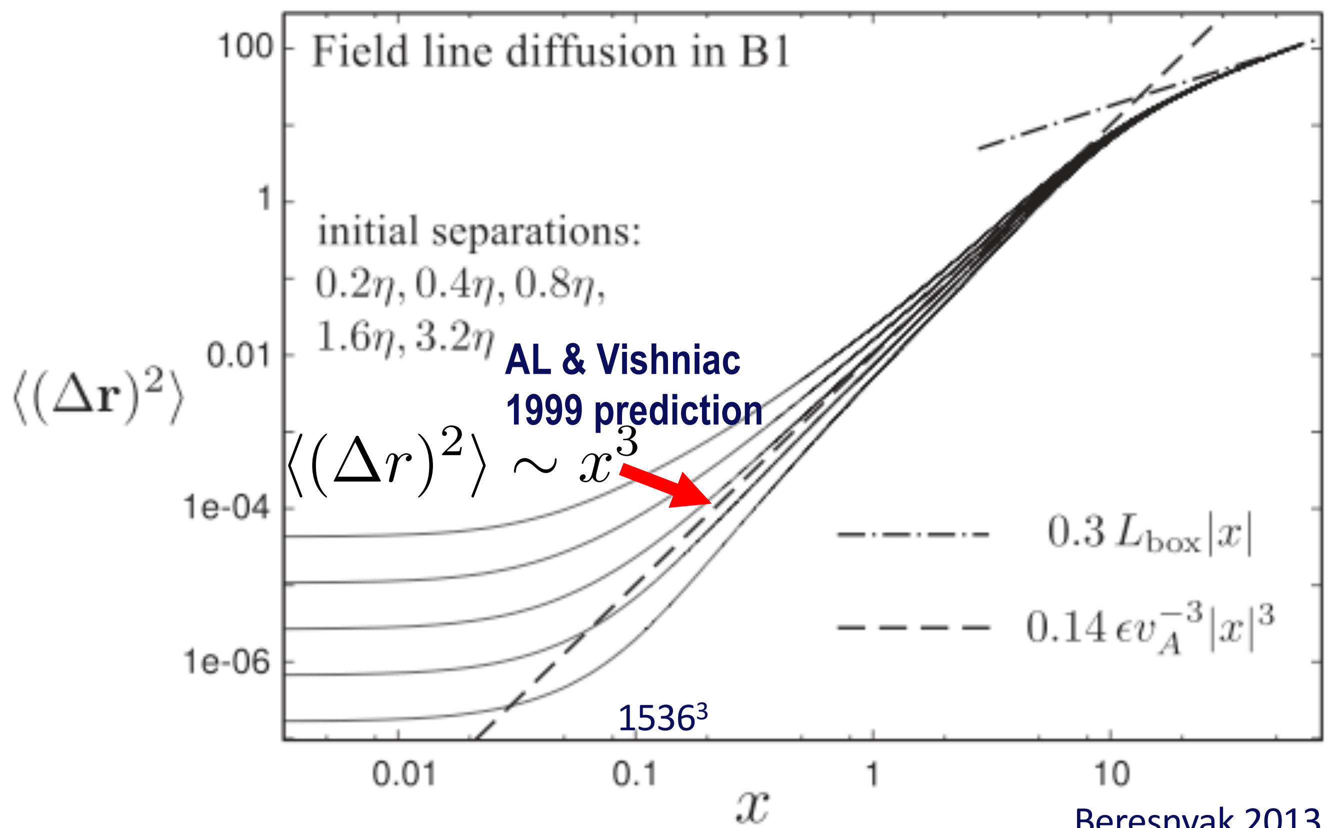
$$\langle |y_1(s) - y_2(s)|^2 \rangle \sim s^3 \, \mathrm{M_A}^4$$

AL & Vishniac 1999

$M_A = V_{injection}/V_{Alfven}$ Is Alfven Mach number



Superdiffusion is confirmed by tracing magnetic field line separation

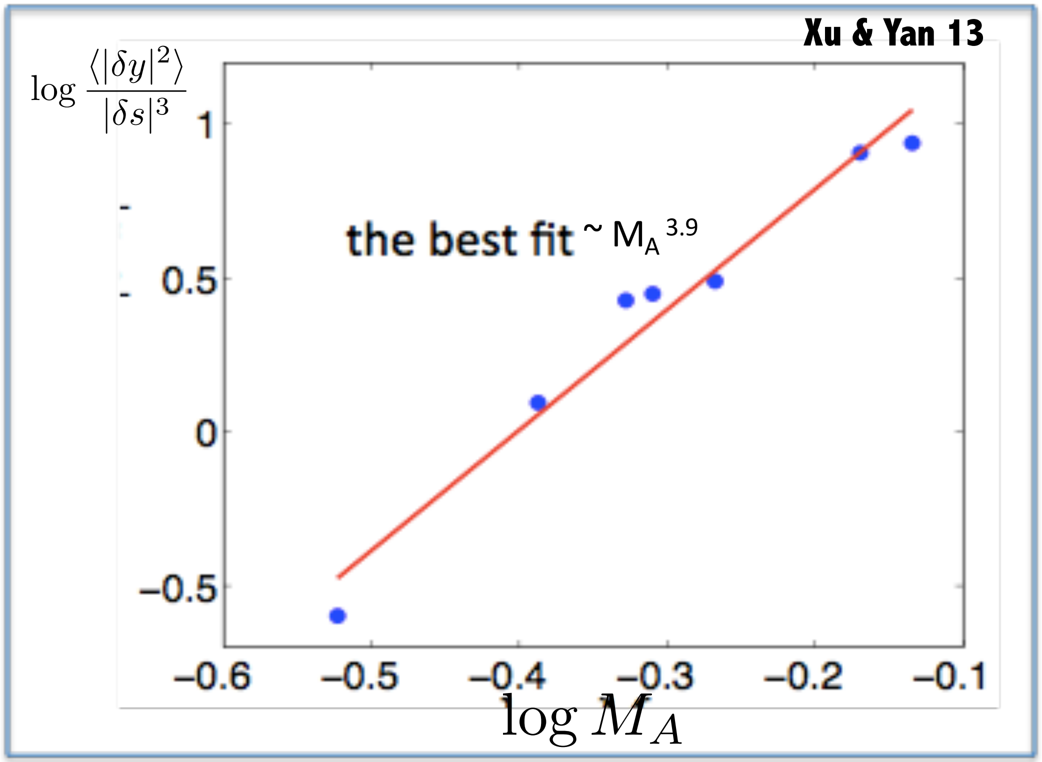


Beresnyak 2013

… as well as with tracing particles following magnetic field

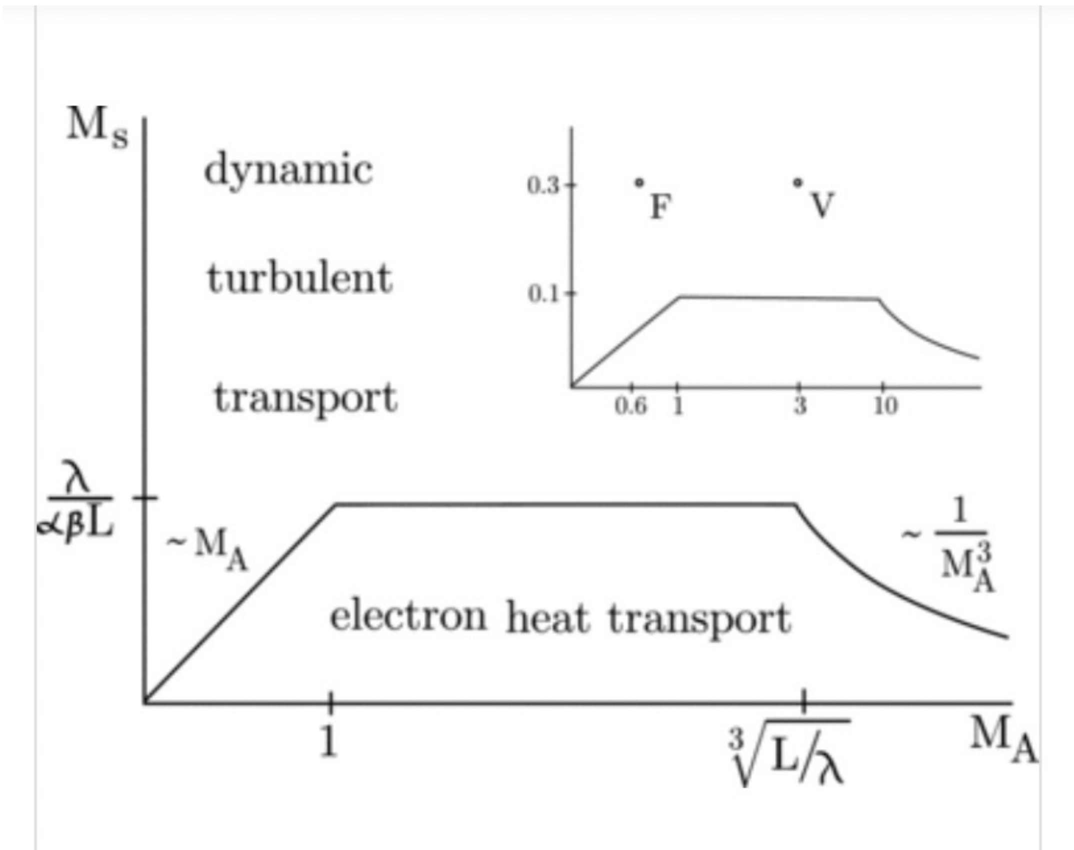
$$\langle |y_1(s) - y_2(s)|^2 \rangle \sim s^3 M_A^4$$

$$M_A = \frac{V_{inj}}{V_A}$$



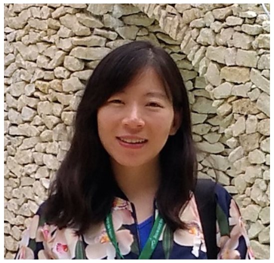
Changes CR acceleration in shocks (AL & Yan 2014)

For clusters of galaxies the turbulent transport enabled by reconnection diffusion is the most important



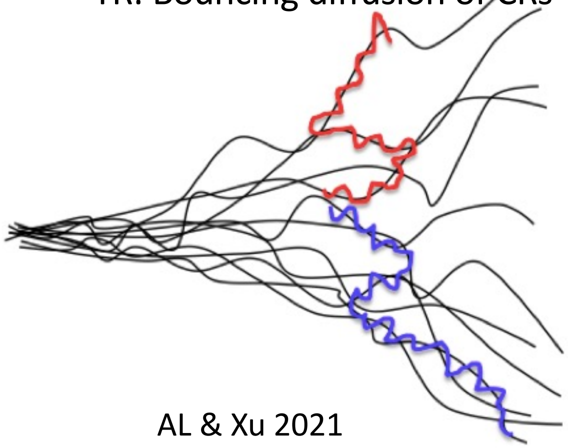
AL 2006

Magnetic wandering enables efficient second-order Fermi and magnetic bottle removal



Siyao Xu

TR: Bouncing diffusion of CRs



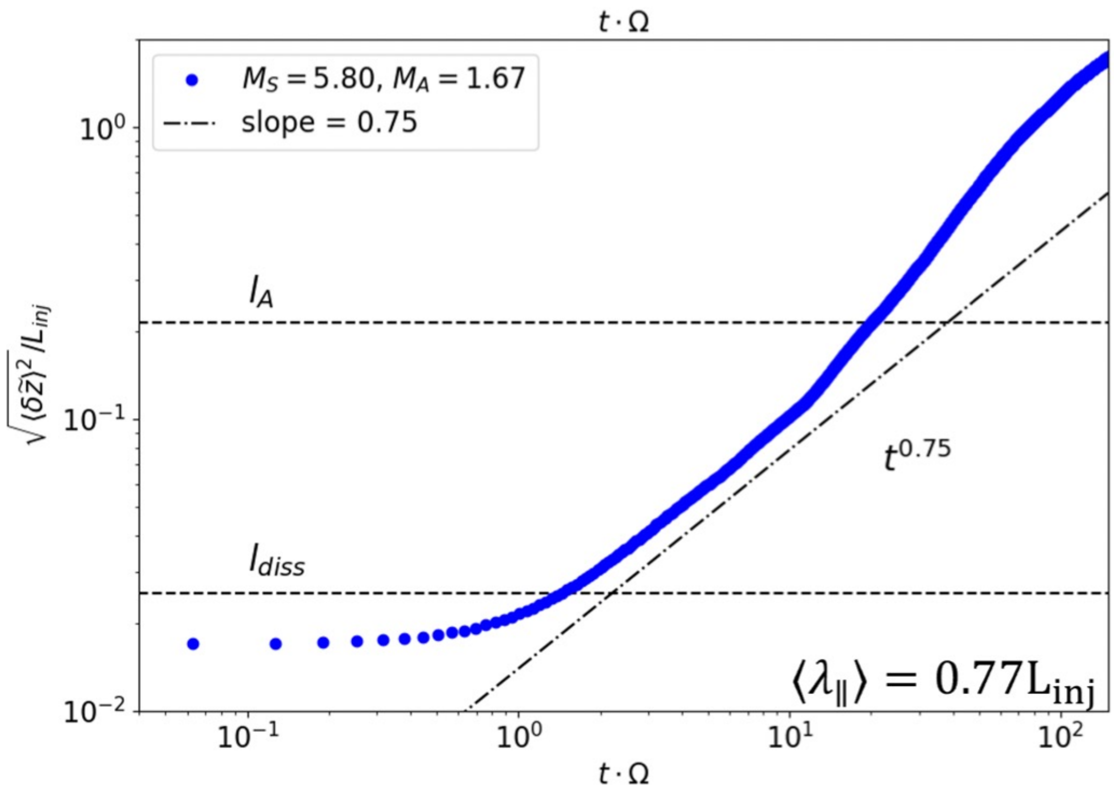
AL & Xu 2021

Due to superdiffusion particles are not trapped by magnetic mirrors and propagate perpendicular to B as $y^2 \sim s^{5/2}$ and experience 2nd order Fermi bouncing acceleration

Al & Xu 2022

Xu 2021 explanation of the gamma-ray emission from supernovae remnants

In the presence of scattering the perpendicular diffusion law changes

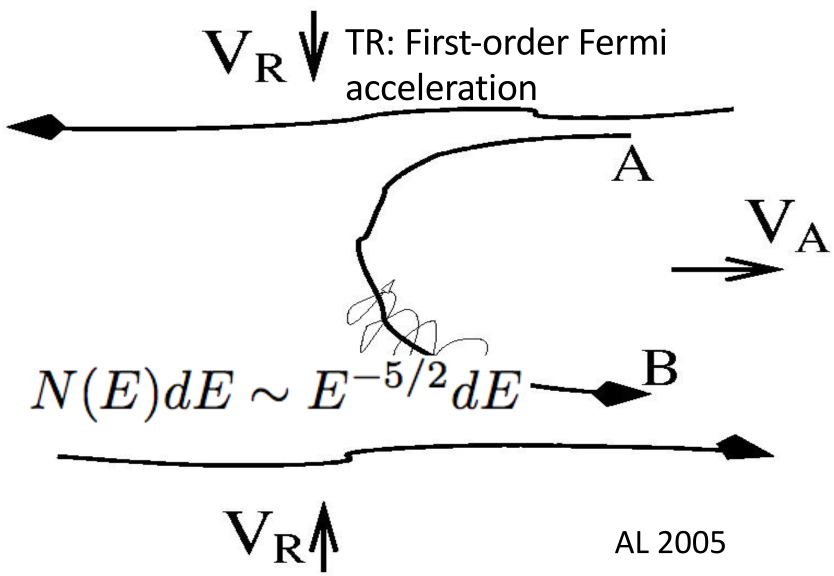


Yue Hu

Hu, AL & Xu 2022

TR: First order Fermi acceleration of Cosmic Rays (CRs) in 3D

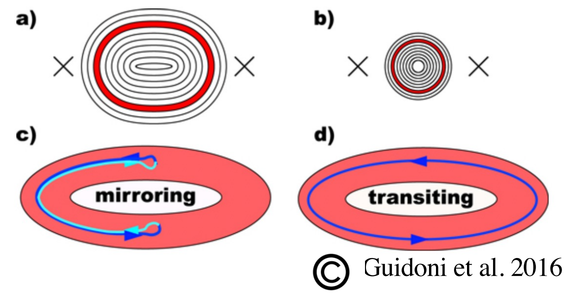
Acceleration in LV99 reconnection:



De Gouveia Dal Pino & AL 2005

Parallel momentum increases due to bouncing from convergent magnetic mirrors

Alternative idea of acceleration in 2D islands by Drake et al. 2006:

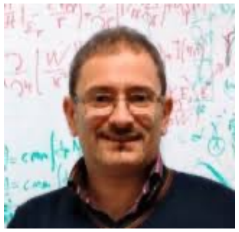


"2D islands are graveyards of CRs"
L. Sironi 2022

1.5 order Fermi Acceleration by reconnection in MHD turbulence

Within reconnection regions in turbulent flow CRs momentum increase $\boldsymbol{\delta p > p}$

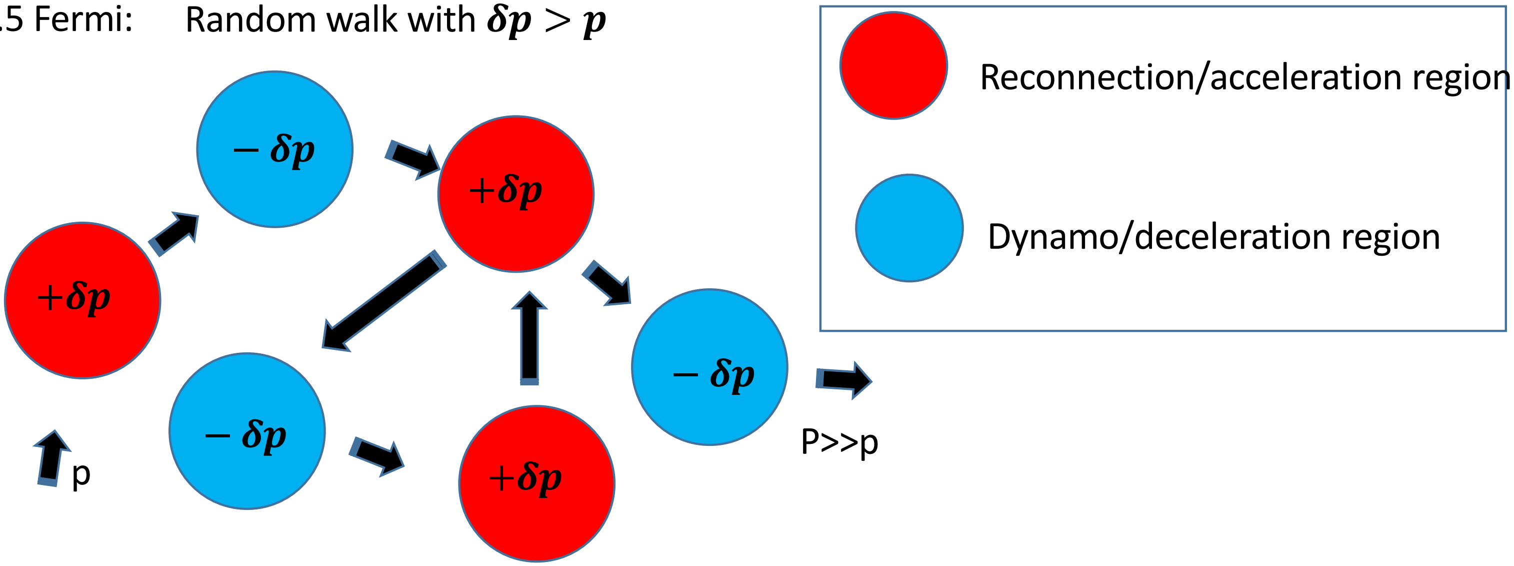
1.5 order Fermi acceleration: random walk with large increments $\boldsymbol{\delta p > p}$



G. Brunetti

In MHD turbulence kinetic energy and magnetic energy constantly transfer into each other

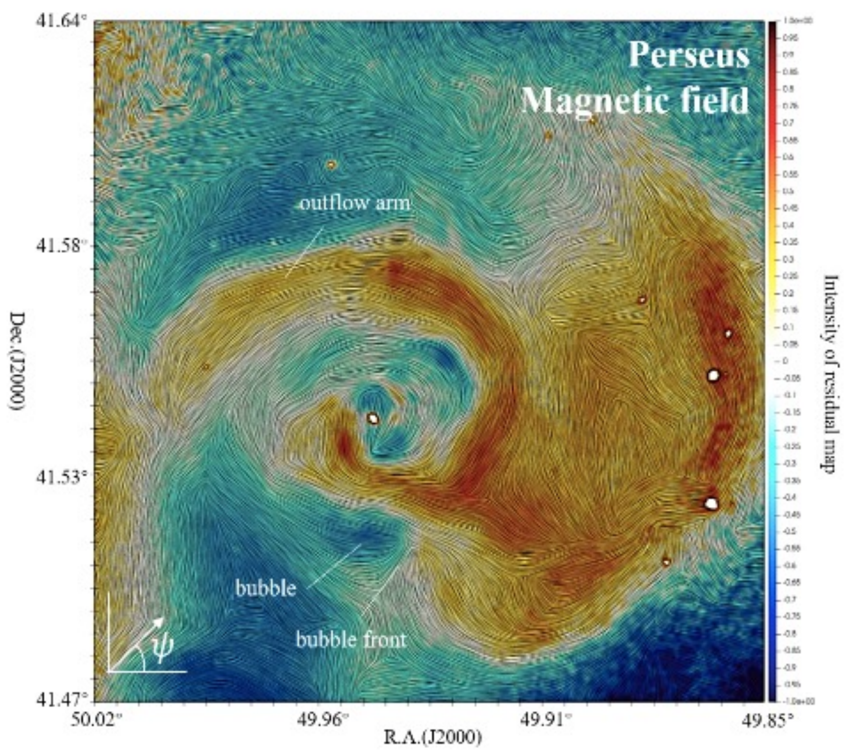
1.5 Fermi: Random walk with $\boldsymbol{\delta p > p}$

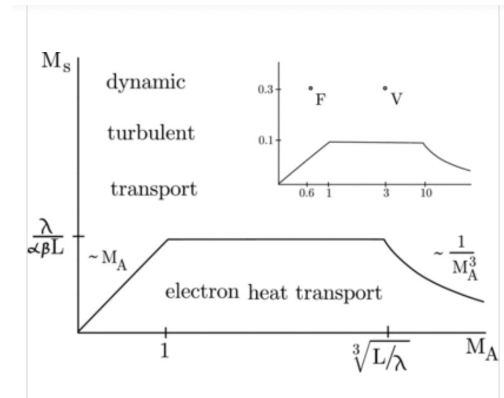


Brunetti & AL 2016 first application to clusters of galaxies electron acceleration, explaining spectra of gamma-ray bursts in Xu & Zhang 2020….

Summary

Gradient technique opens a new way to study magnetic fields in galaxy clusters.
Magnetic field deeply affects the physics of ICM.





Differential Measure Approach instead of DCF

Using not dispersions by differential measures, i.e. *<u>small R separation</u>* structure function of centroid velocity

$$D_v(R) = \langle (v(X+R) - v(X))^2 \rangle$$

and angle instead of σ_v

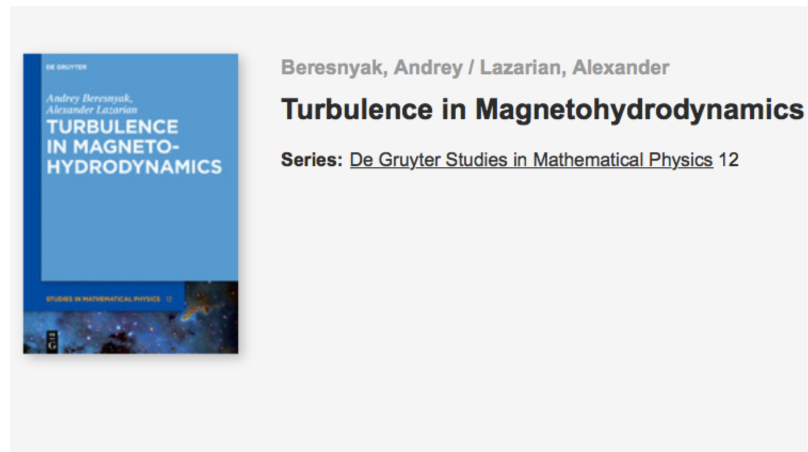
$$D_\phi(R) = \langle (\phi(X+R) - \phi(X))^2 \rangle$$

instead of dispersions of σ_ϕ

This allows:

1. Decrease the amount of data required.
2. Measure B for $B_{mean} < \delta B$
3. Remove velocity regular distortions due to galactic shear.
4. Remove B-field distortions due to gravity.
5. Study variations of $B_{\perp,mean}$

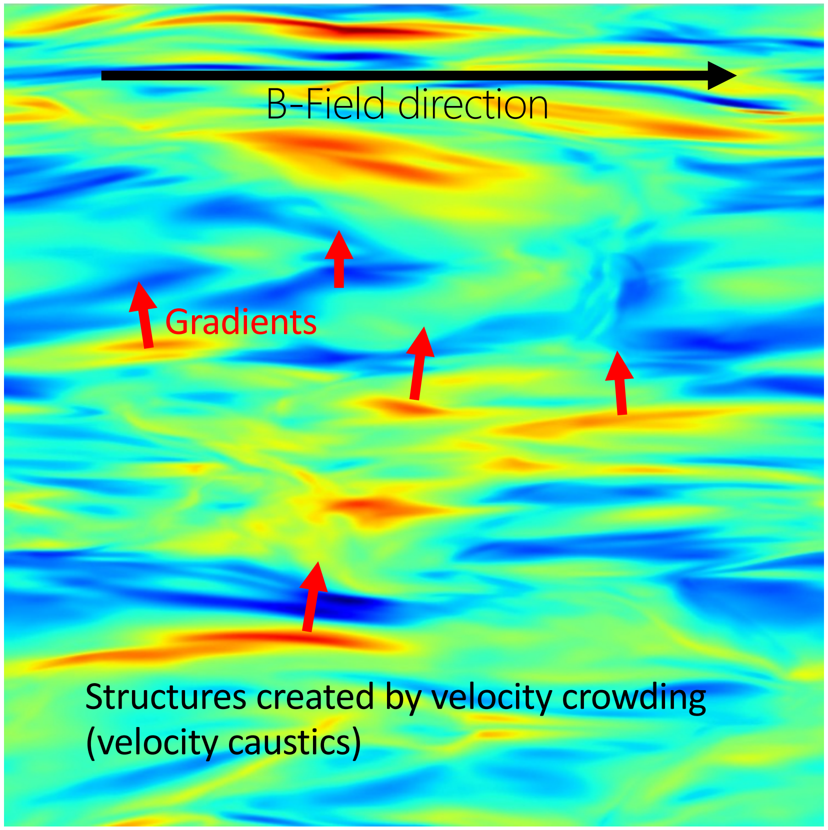
Using the theory of MHD turbulence rather than linear Alfven waves



This allows obtaining analytical expressions for realistic turbulent media

Implemented in AL, Yuen & Pogosyan (2020, 2021)

B-field direction can be revealed by gradients in velocity channel maps



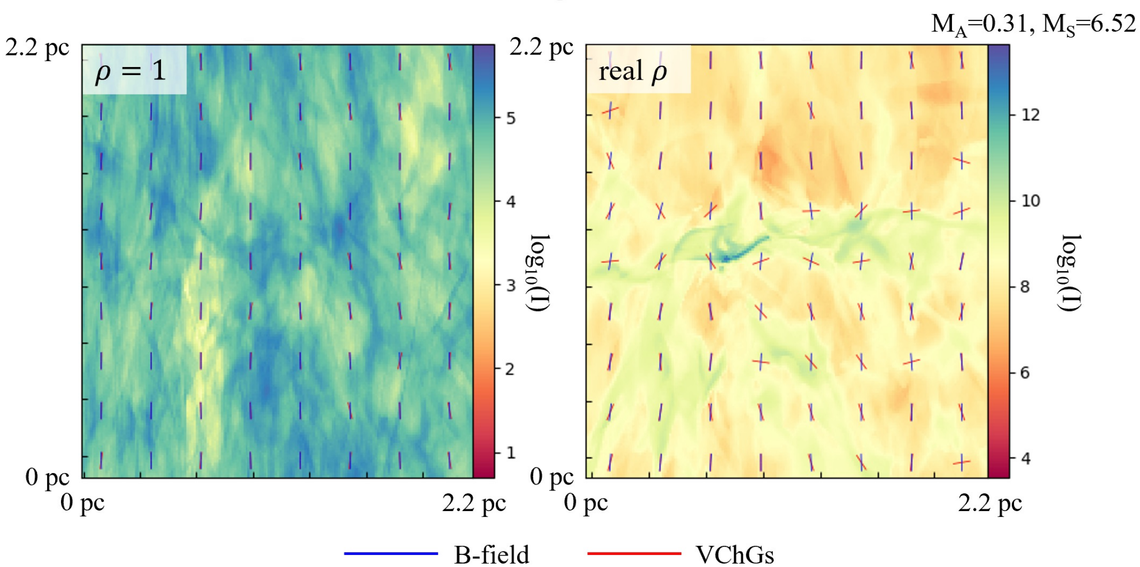
AL & Yuen 2018

We turn velocity gradients 90 degrees to trace magnetic field direction

Filaments are clearly seen in channel maps obtained with *incompressible* simulations

The controversy of what is seen in channel maps can be resolved by using the Velocity Decomposition Algorithm (VDA)

Talk tomorrow by Ka Ho Yuen



$$p_v = p - (\langle pI \rangle - \langle p \rangle \langle I \rangle) \frac{I - \langle I \rangle}{\sigma_I^2}$$

$$p_d = p - p_v$$

$$= (\langle pI \rangle - \langle p \rangle \langle I \rangle) \frac{I - \langle I \rangle}{\sigma_I^2}$$

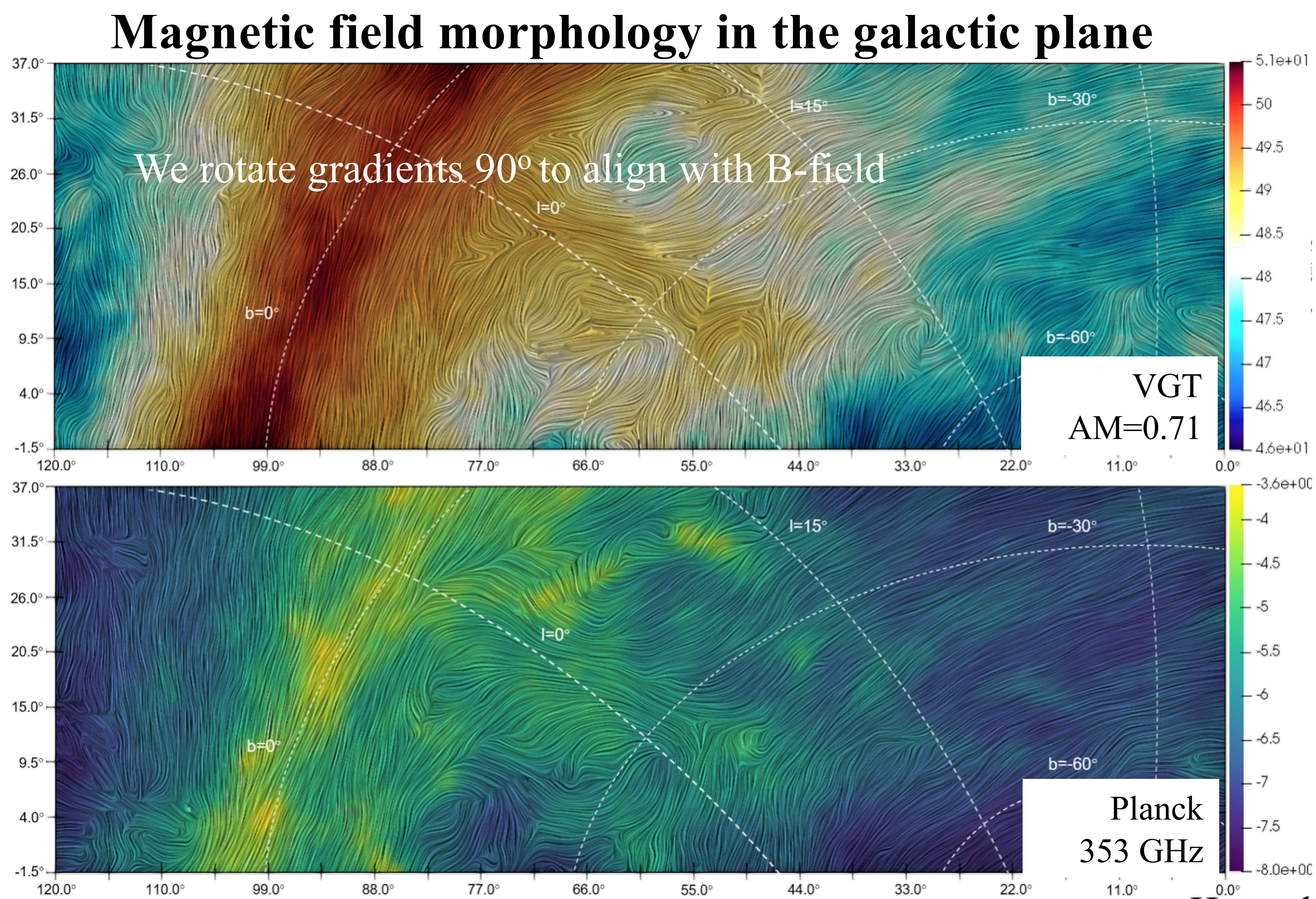
p_v is the channel intensity due to velocity caustics

p_d is the channel intensity due to density effects

Distortions in Channel Maps are induced by densities. VDA removes the contribution of density.

Yuen, Ho & AL 2021

Good correspondence with Planck polarization polarization

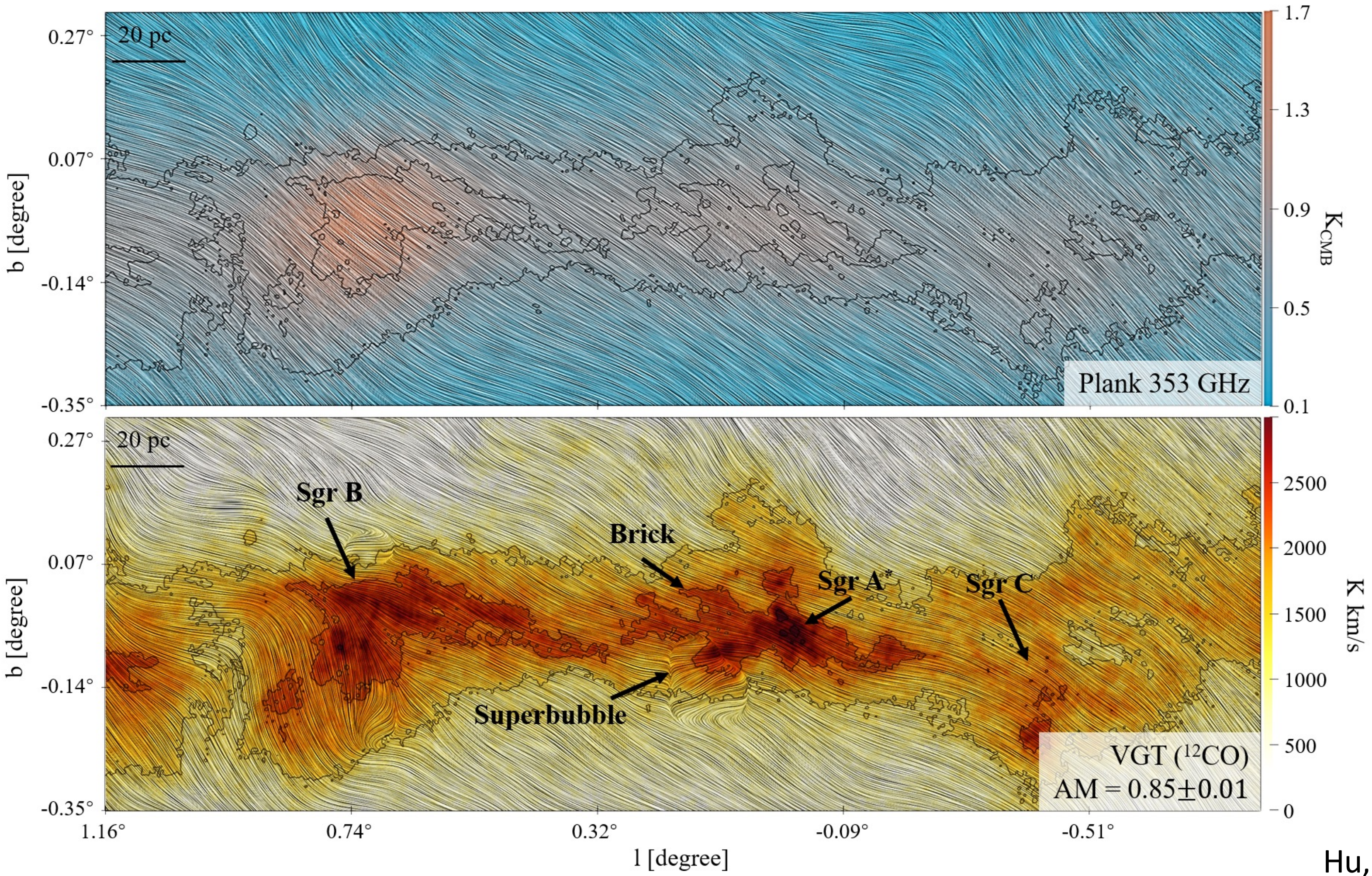


Hu et al. (2020)

More in the talk tomorrow by Dmitri Pogosyan

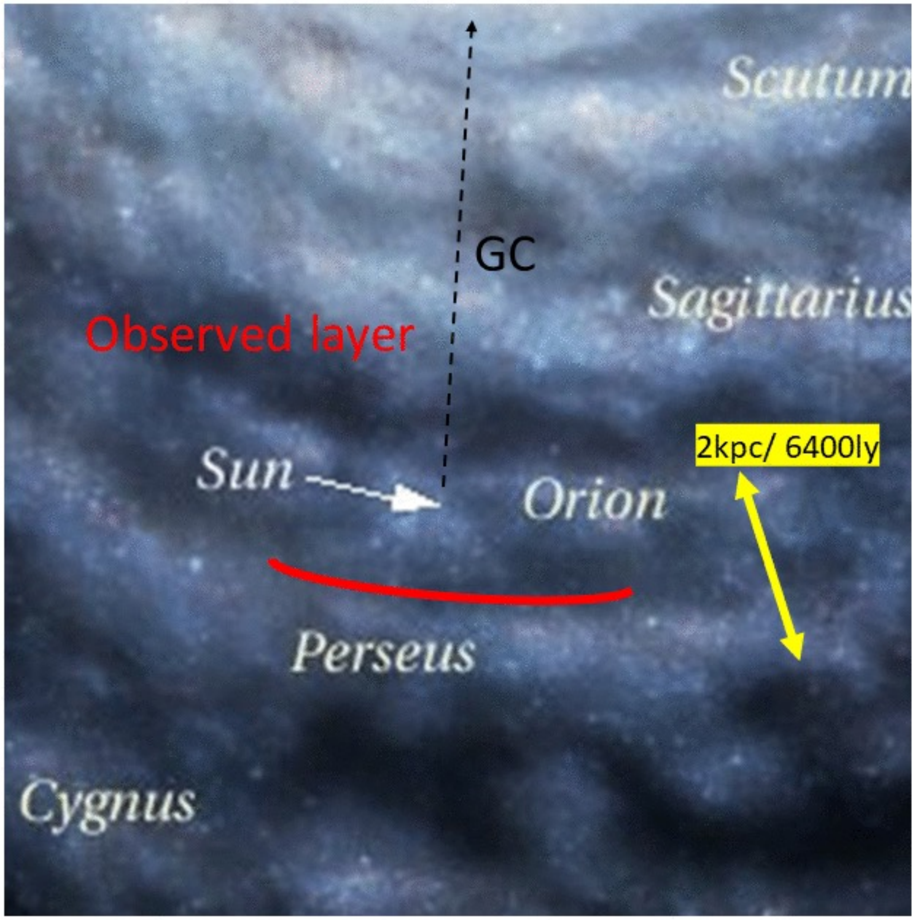
Lu, AL, Pogosyan 2020

Gradients and polarization for the Central Molecular Zone

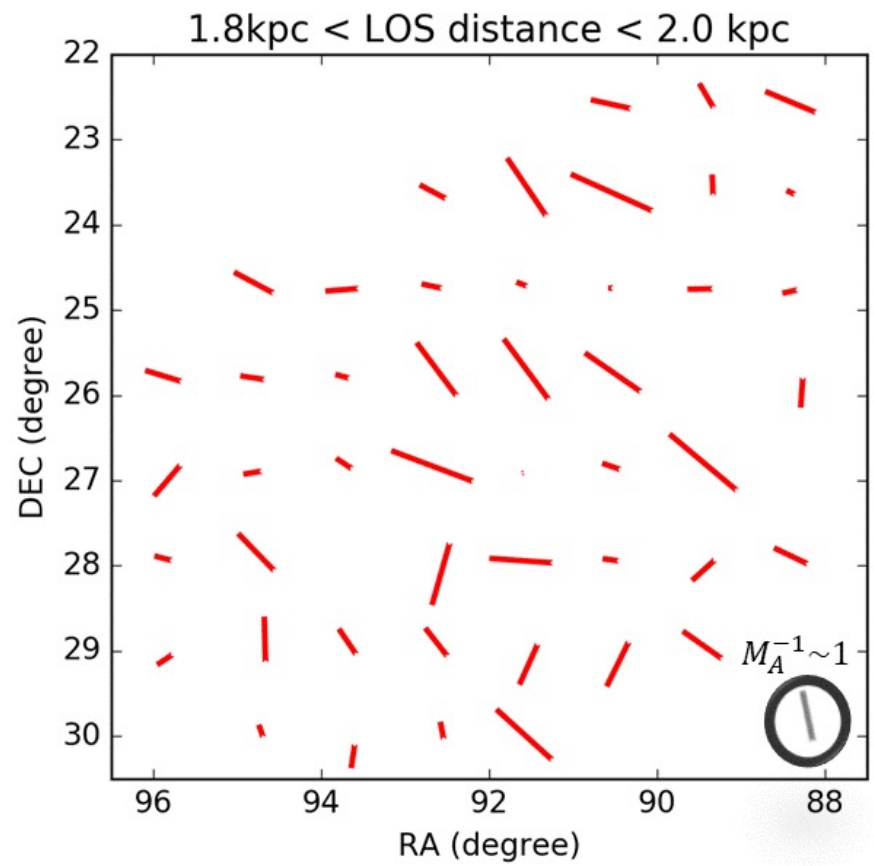


Hu, AL & Wang 2021

More information compared to polarization: it is possible to study 3D structure of magnetic field in galactic disk

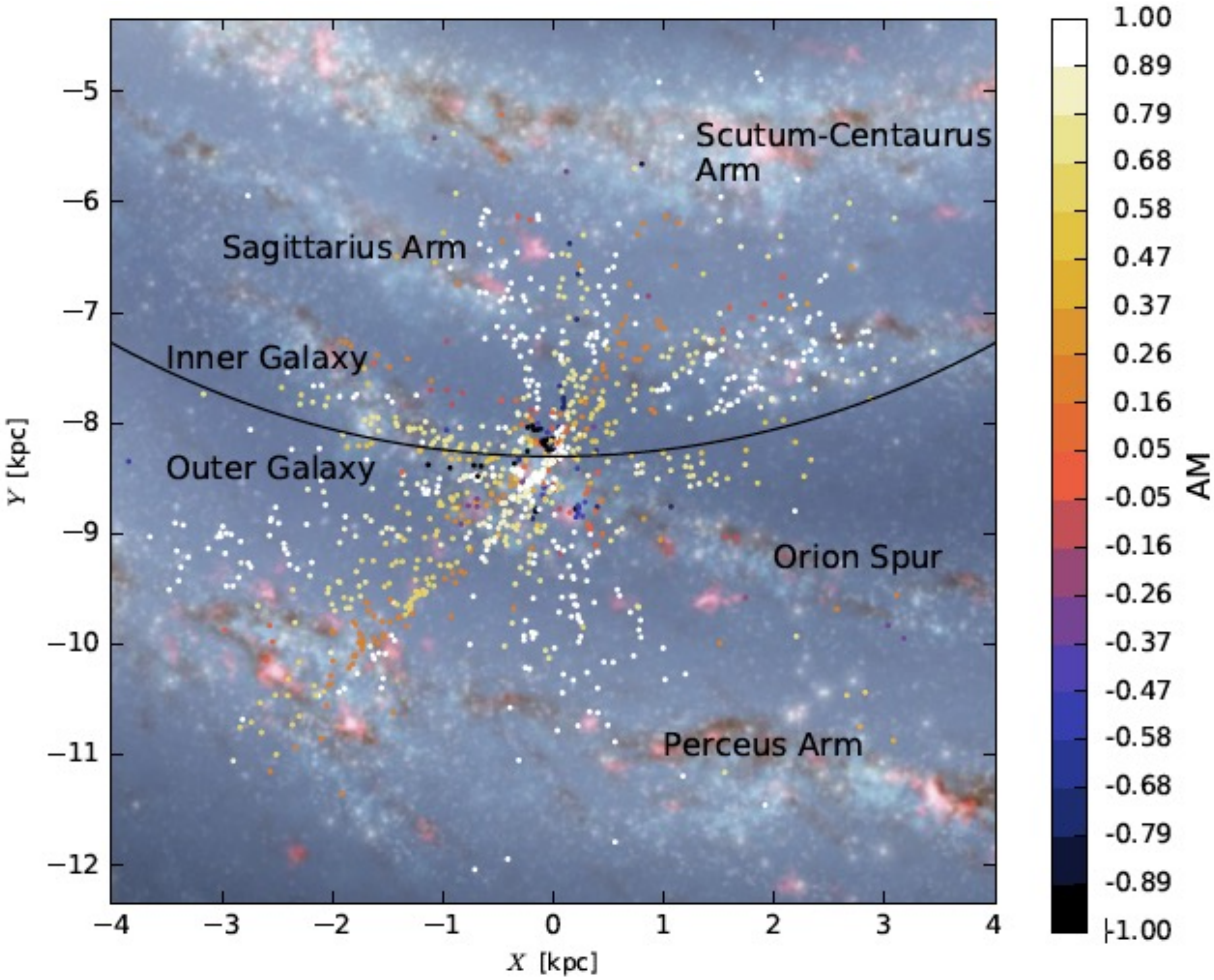


Yuan et al. 2018



Vector length is proportional to B

3D B-field distribution corresponds well to starlight polarization

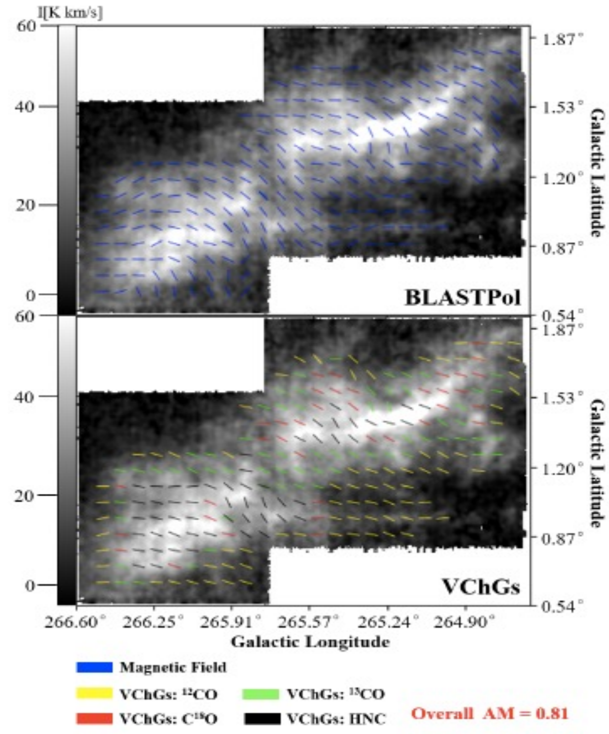


Star polarization versus predictions with our 3D model of galactic magnetic field. This demonstrates that the model is correct!

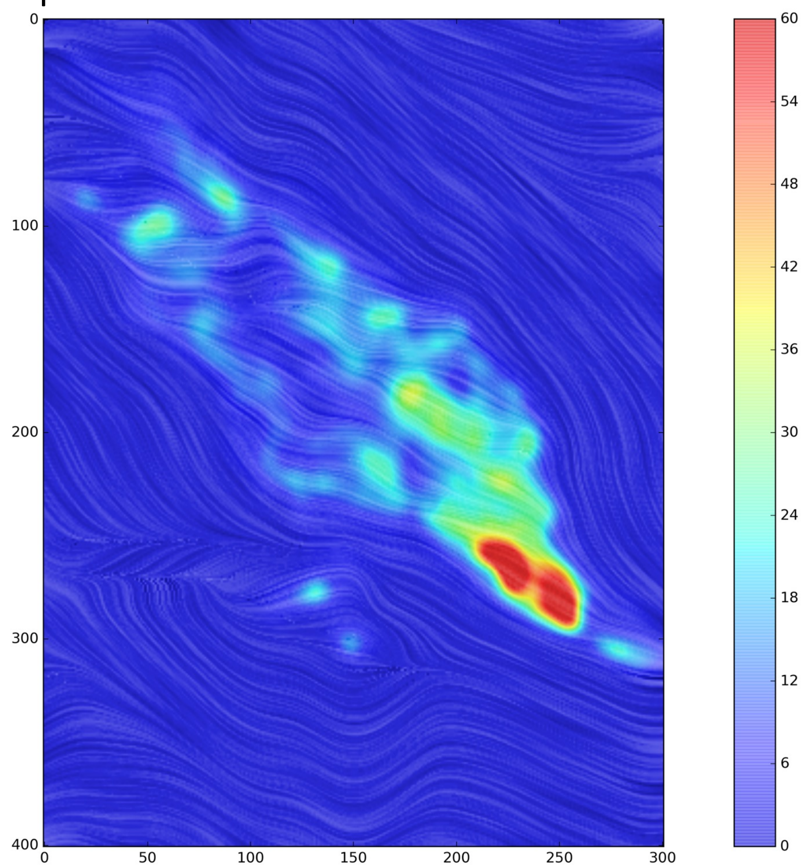
Gonsalvez-Casanova & AL 2018

Velocity gradients provide unique ways to study B-fields

3D structure of B-field with different tracers

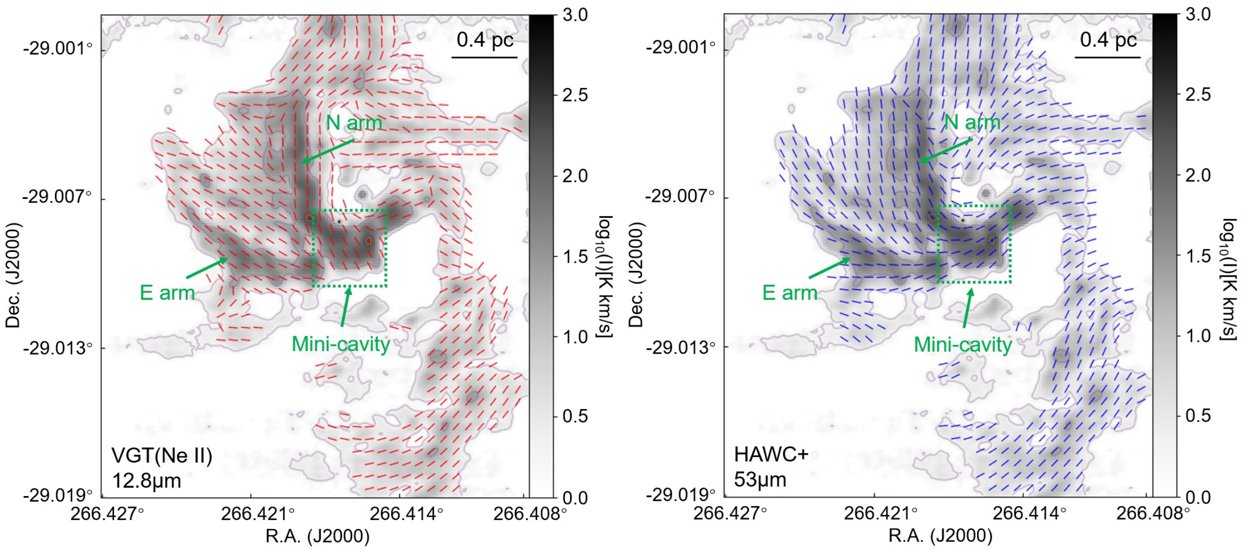


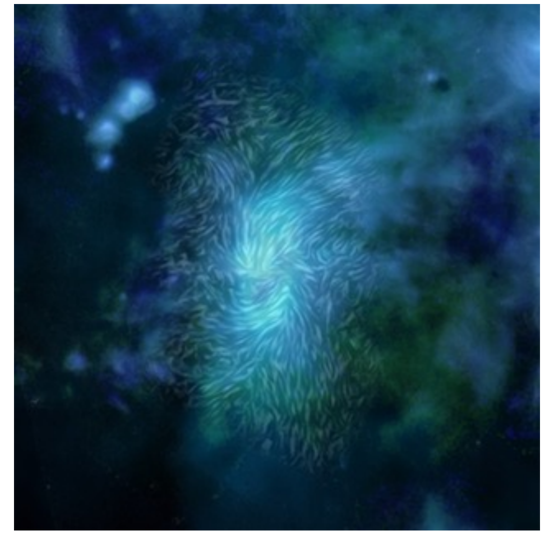
B-field of Smith high velocity cloud too faint for polarization

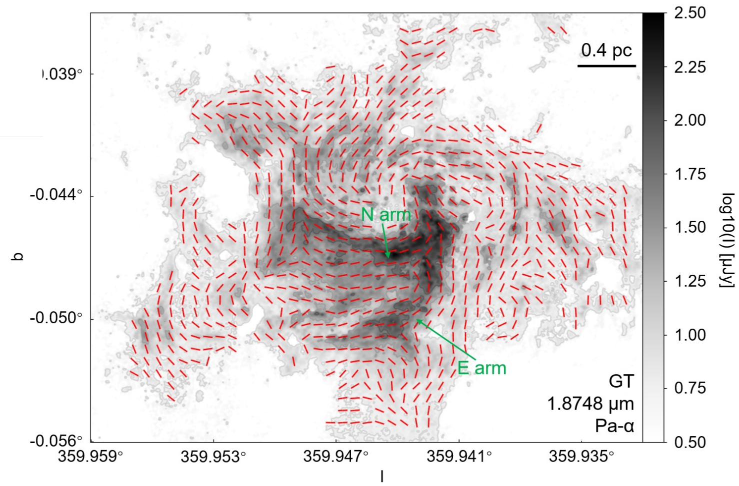


Hu at al. 2019

Gradients reveal that magnetic field in different phases varies in direction







Galactic center region

Hu, AL & Wang 2021